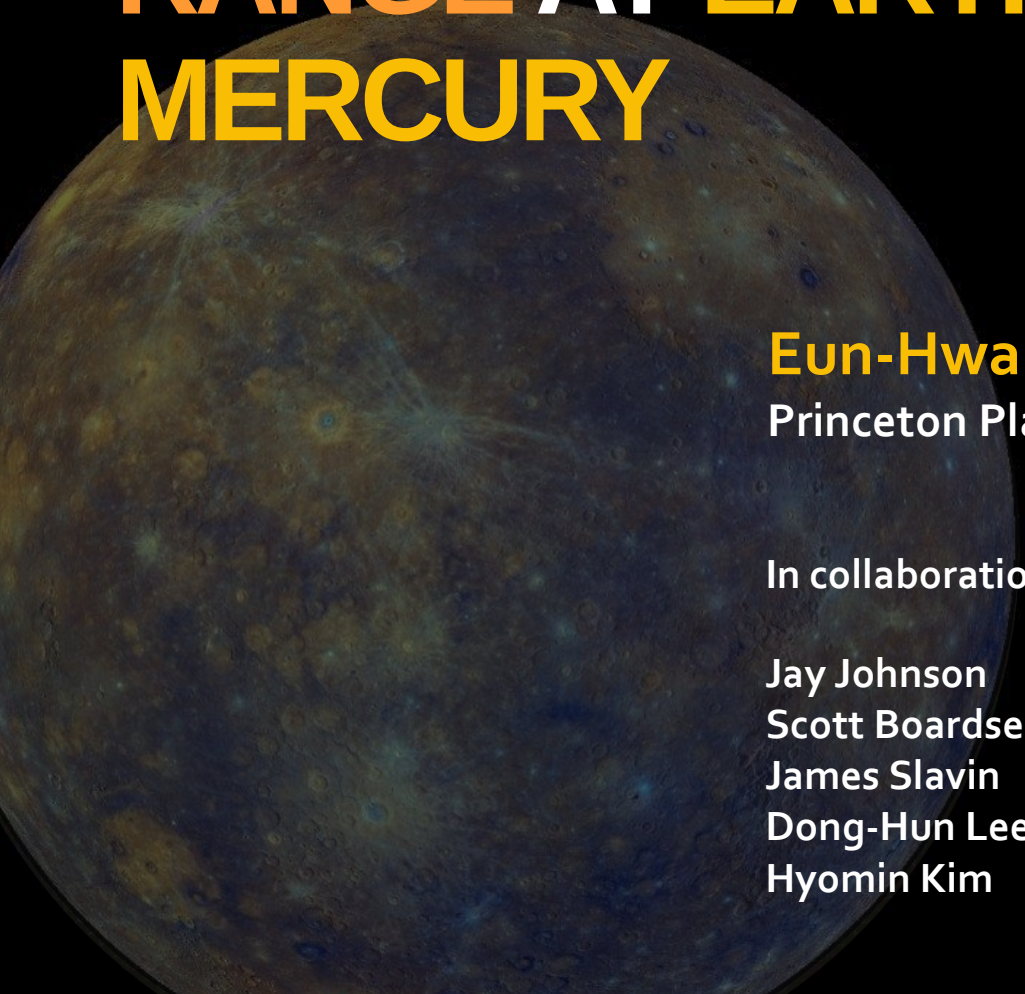
WAVES IN THE ION CYCLOTRON FREQUENCY RANGE AT EARTH AND MERCURY

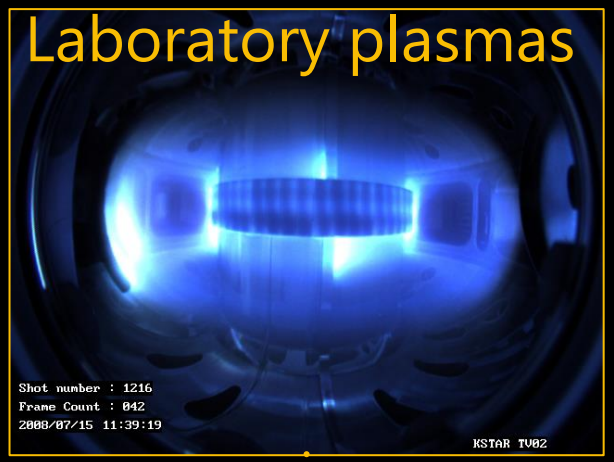


Eun-Hwa Kim
Princeton Plasma Physics Laboratory

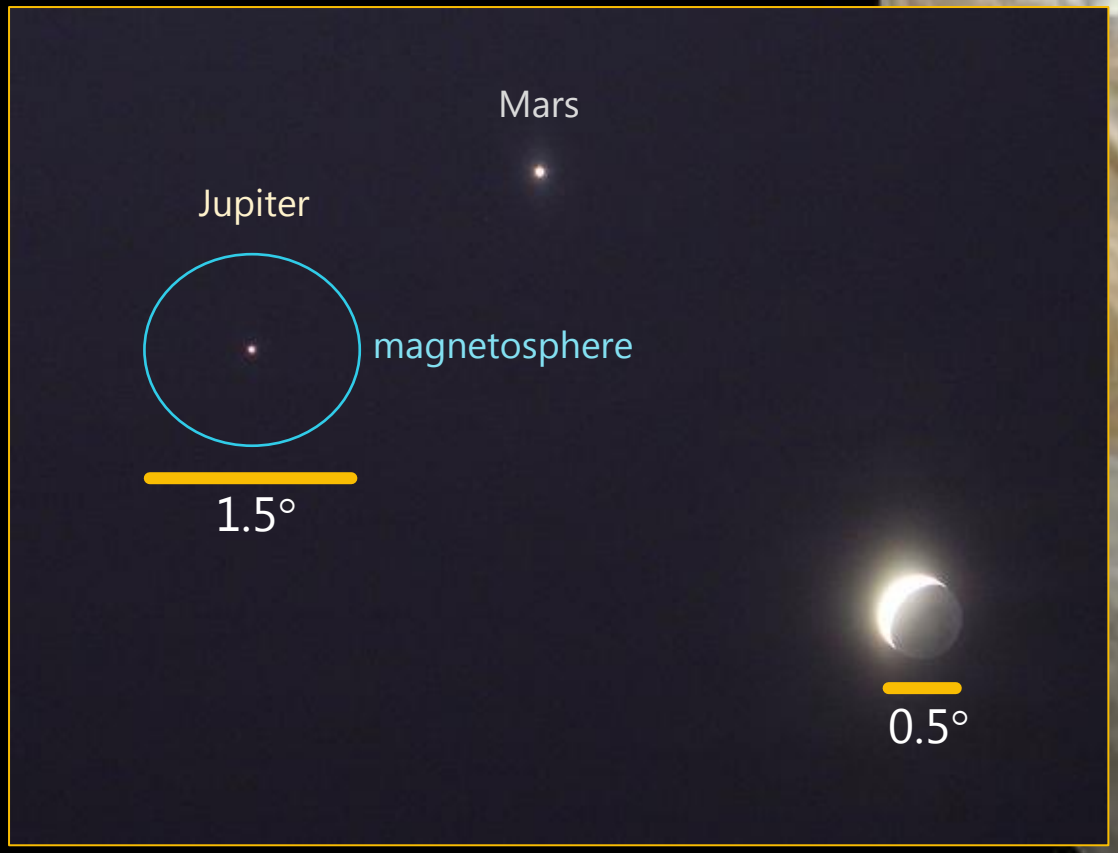
In collaboration with

Jay Johnson	Princeton Plasma Physics Laboratory
Scott Boardsen	NASA/GSFC, University of Maryland
James Slavin	University of Michigan
Dong-Hun Lee	Kyung Hee University, Korea
Hyomin Kim	New Jersey Institute of Technology

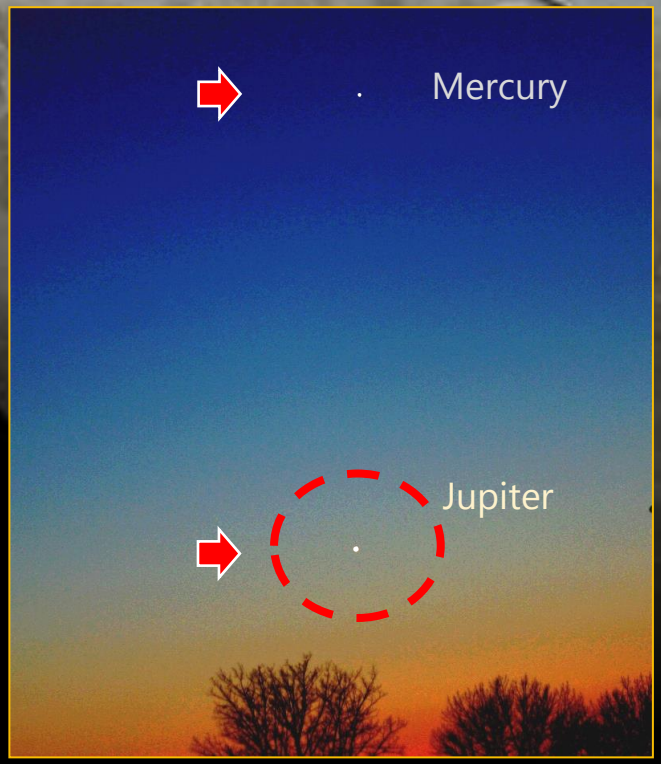
Laboratory plasmas

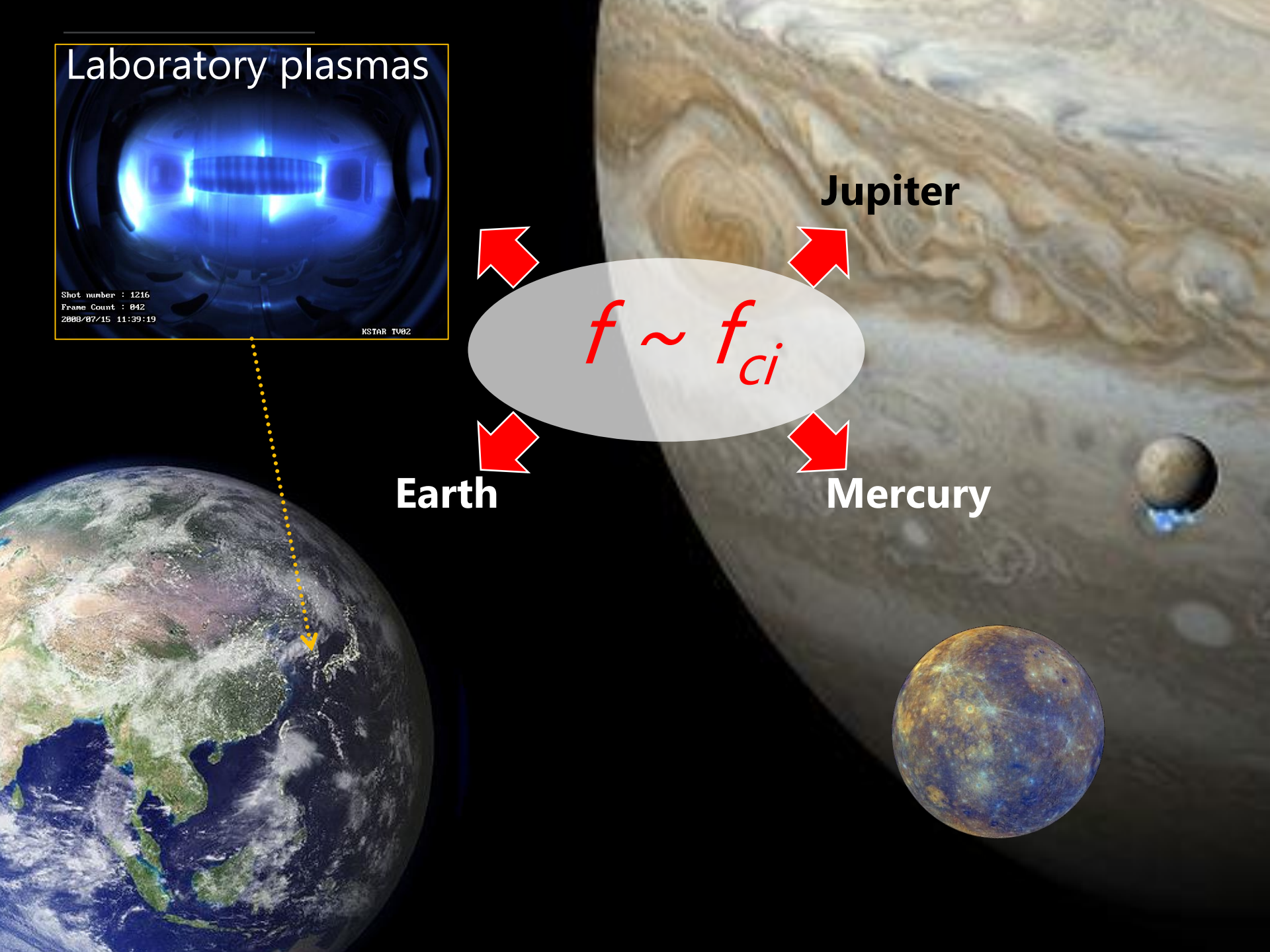


Mercury



Mercury




Laboratory plasmas
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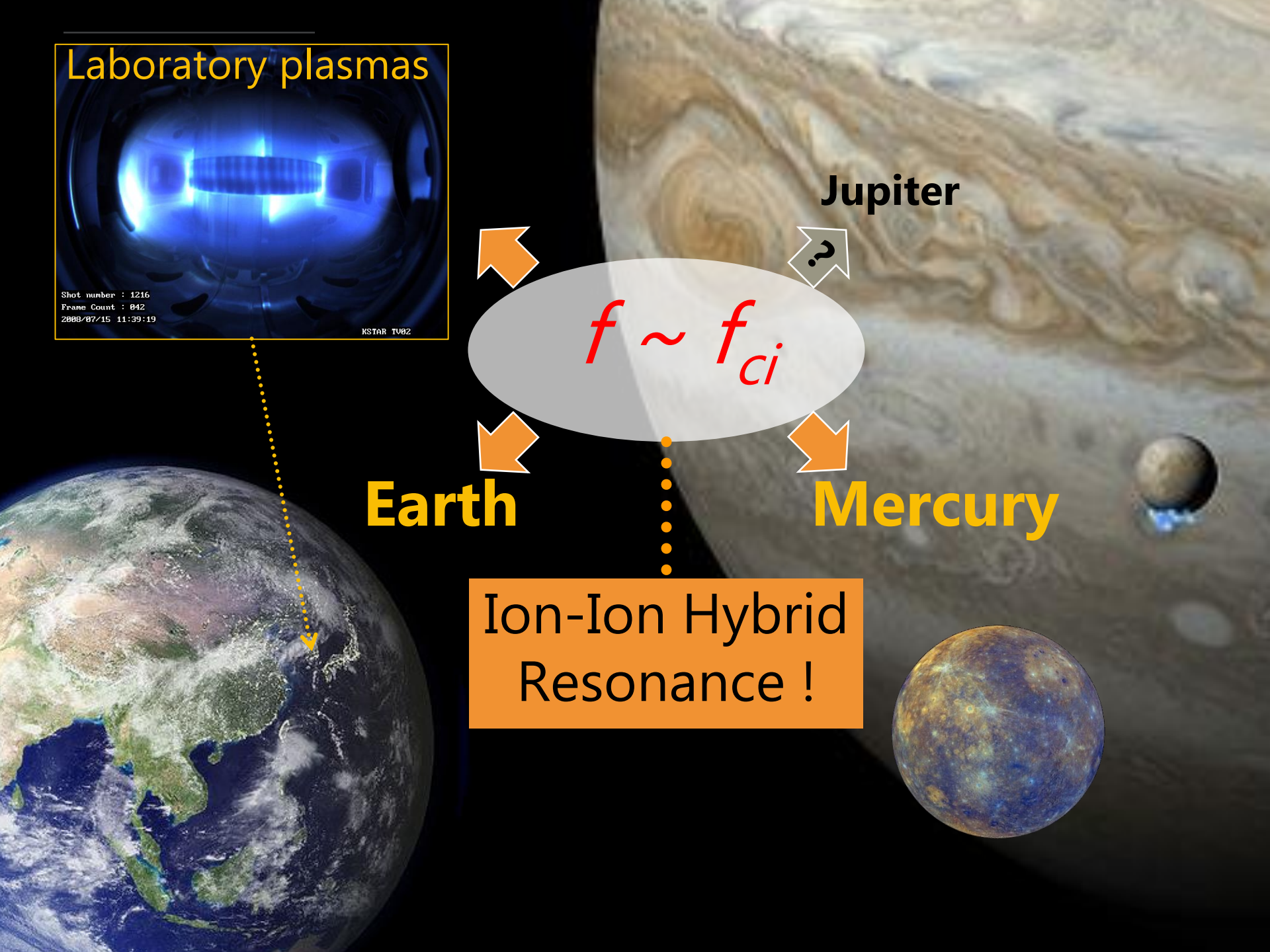
Frame Count : 042
2008/07/15 11:39:19
KSTAR TV02
Jupiter
$f \sim f_{ci}$
Earth
Mercury


Laboratory plasmas
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KSTAR TV02
Jupiter
?
$f \sim f_{ci}$
Earth
Mercury
Ion-Ion Hybrid Resonance !

@ Mercury

- What are the observed ULF waves? How can they propagate to higher magnetic latitude?

@ Earth

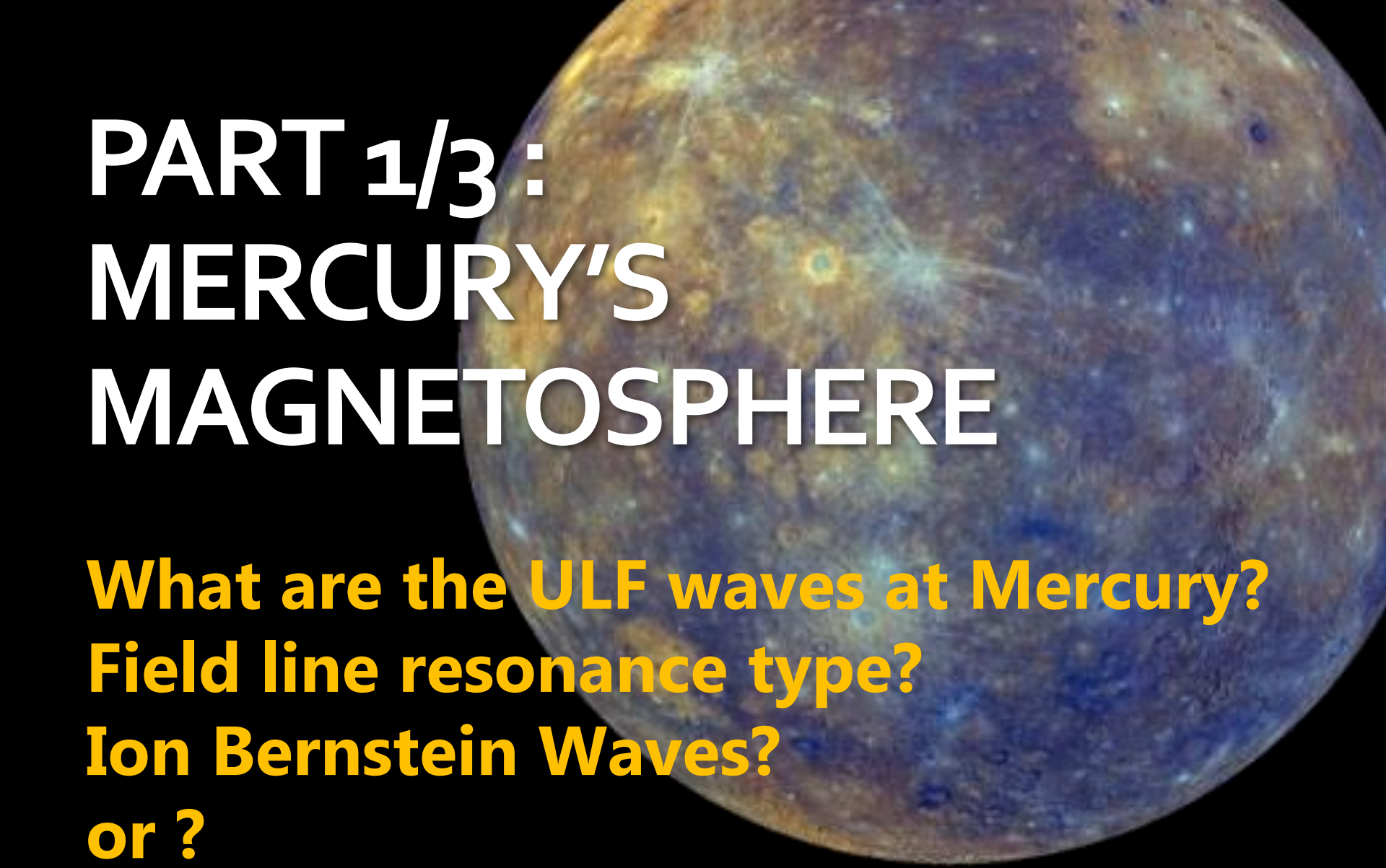
- How are linearly polarized EMIC waves generated?

@ Mercury & Earth

- Can we use the detected waves as a diagnostic tool to estimate heavy ion density?

Mode-converted waves
at the Ion-ion hybrid resonance

Application!



PART 1/3 : MERCURY'S MAGNETOSPHERE

What are the ULF waves at Mercury?
Field line resonance type?
Ion Bernstein Waves?
or ?

Mercury's magnetosphere

Dimension

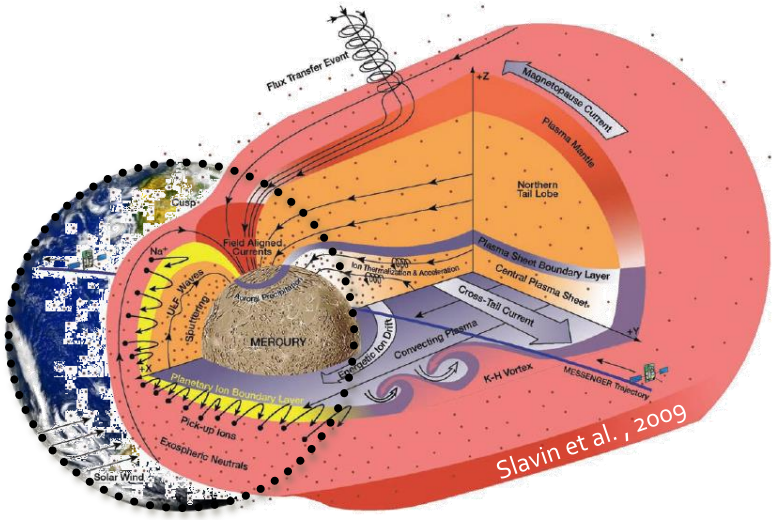
+ Small magnetosphere
  : sub-solar point ~ 1.4 R_M
+ 1.34 R_M ~ 10.8 R_E

Magnetosphere

+ No atmosphere
+ No ionosphere
+ No plasmasphere
+ No co-rotational
  electric field
  to trap cold plasma
+ Na exosphere

Plasma conditions

+ Multi-ion
  - H, He from Sun
  - heavy ions
    : sputtered from surface
      and ionized
+ Hot plasma



Earth

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+ No co-rotational electric field to trap cold plasma
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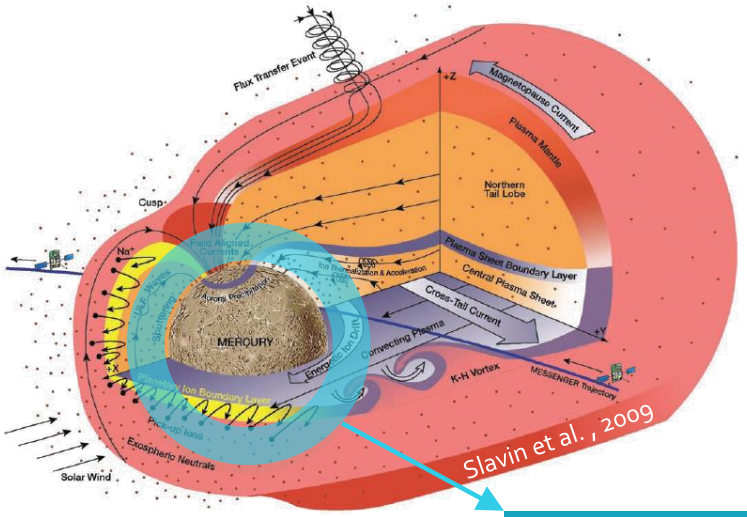
  - heavy ions
    : sputtered from surface and ionized
+ Hot plasma

Missions

+ Mariner 10, 1973
  - three flybys

30 years!

+ MESSENGER, 2004
  - three flybys
  - orbit, 2011
    (period 8hrs, 2012 ~)
  - Magnetometer
    (20 samples/s)
  - No electric field measurement



Slavin et al., 2009

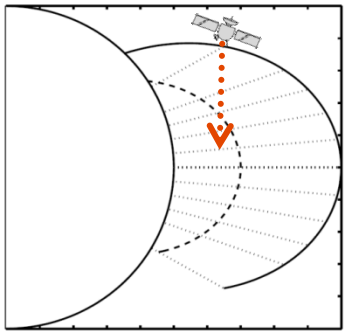
ULF wave observation

Compressional dominant (75%) ? **Transverse dominant (25%)**

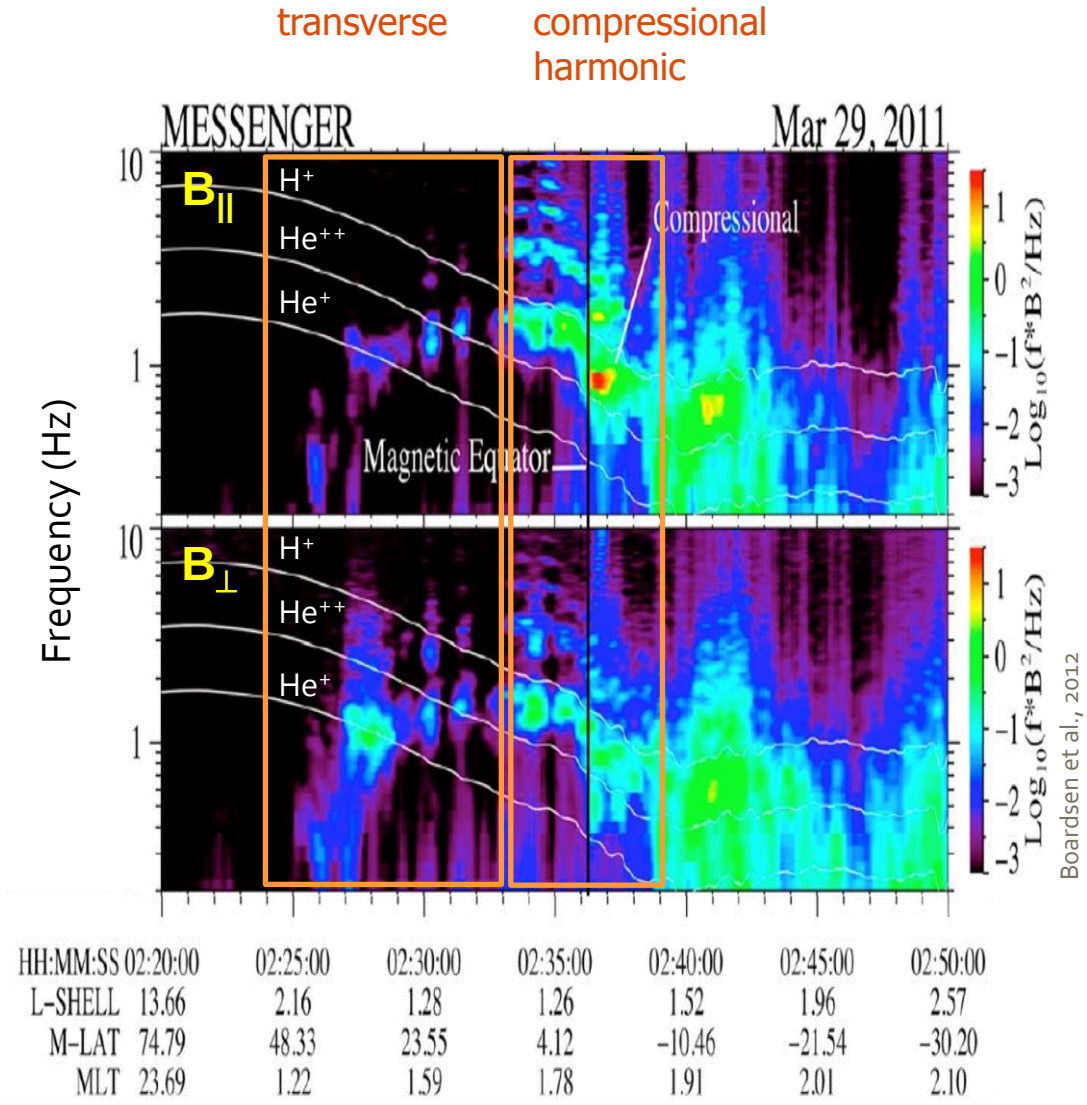
ULF waves at Mercury

MESSENGER

+ Frequency
  - $f_{He} < f < f_H$
+ M-LAT : -5° ~ 45°
  MLT : 1.3 h ~ 1.7 h



+ Equator
  - compressional
  - harmonic
+ Off Equator
  - transverse

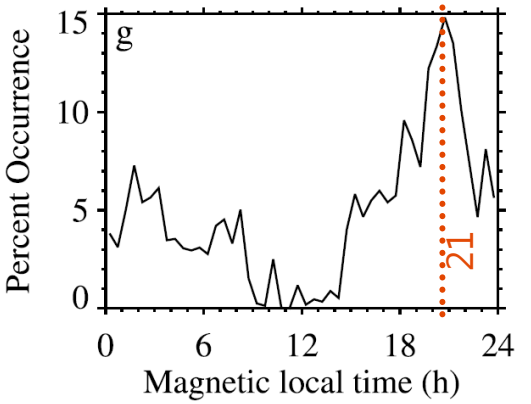


Boardsen et al., 2012

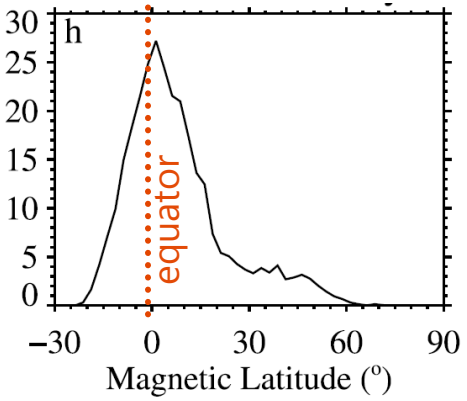
Boardsen et al., 2012, J. Geophys. Res.

Statistical Study using MESSENGER : Percent Occurrence (3/24/11 ~ 09/25/11 : 2.1 Mercury Year)

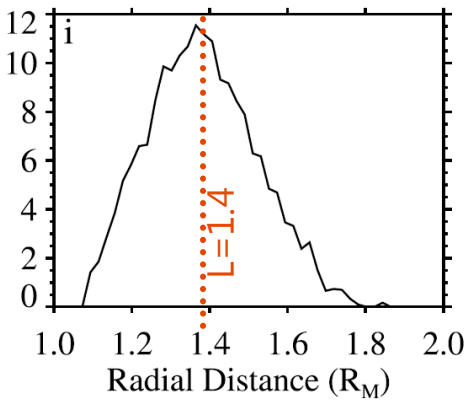
MLT



Magnetic Latitude

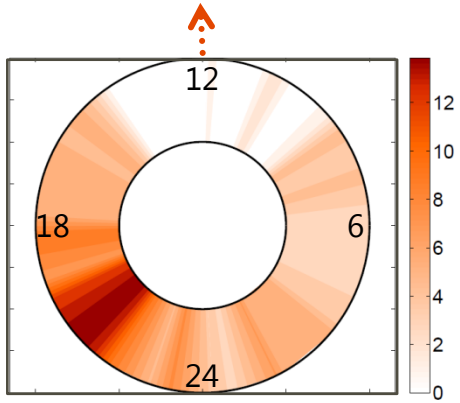


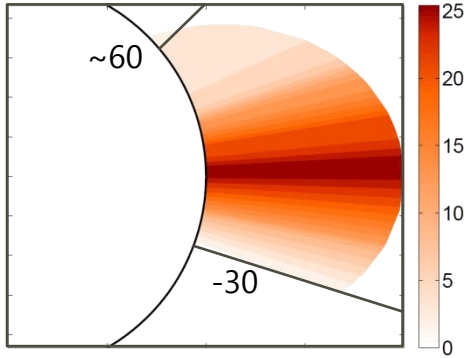
Radial Distance

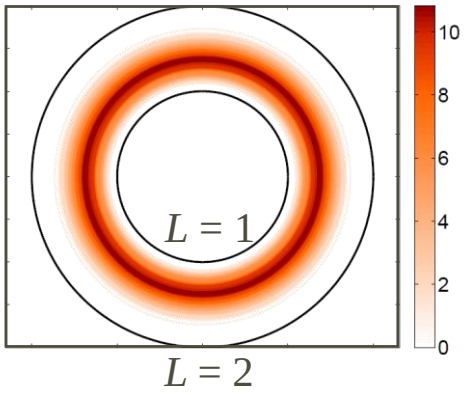


Boardsen et al., 2012

Sunward







Polarization along magnetic latitude

Ratio of Parallel to Total Power

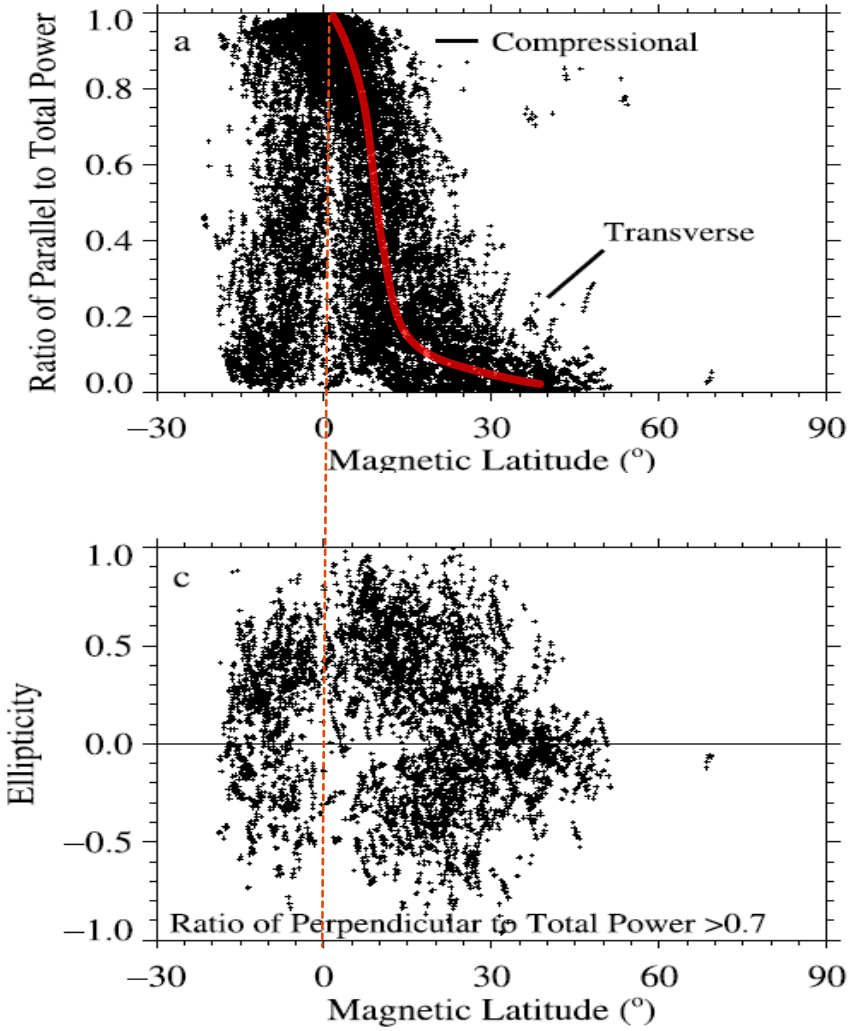
+ Off Equator
  → compressional

+ Equator
  → Transverse

Ellipticity

+ Off Equator
  → linear

+ Equator
  → circular / mixed



Boardsen et al., 2012

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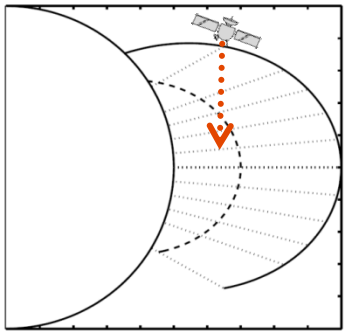

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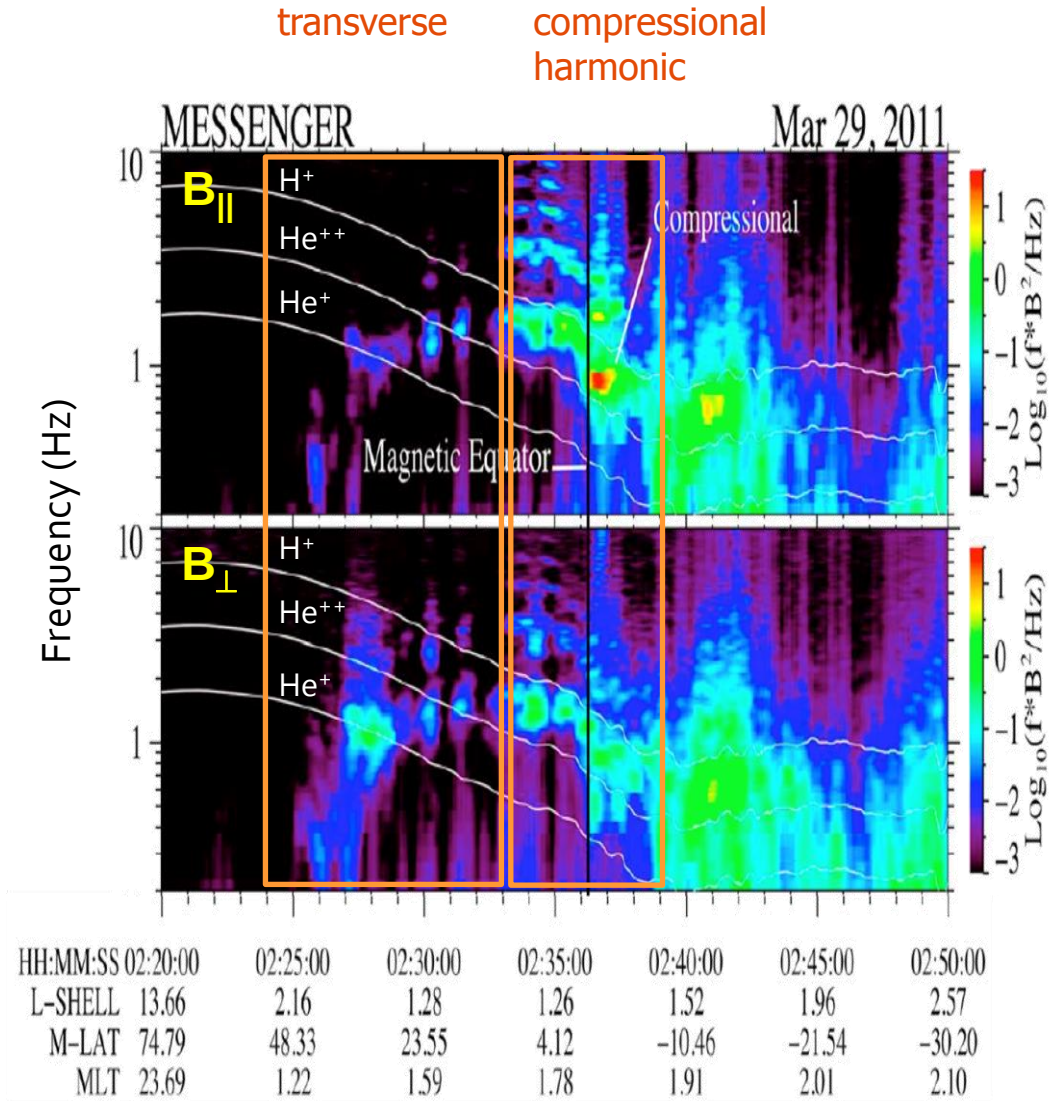

Boardsen et al., 2012

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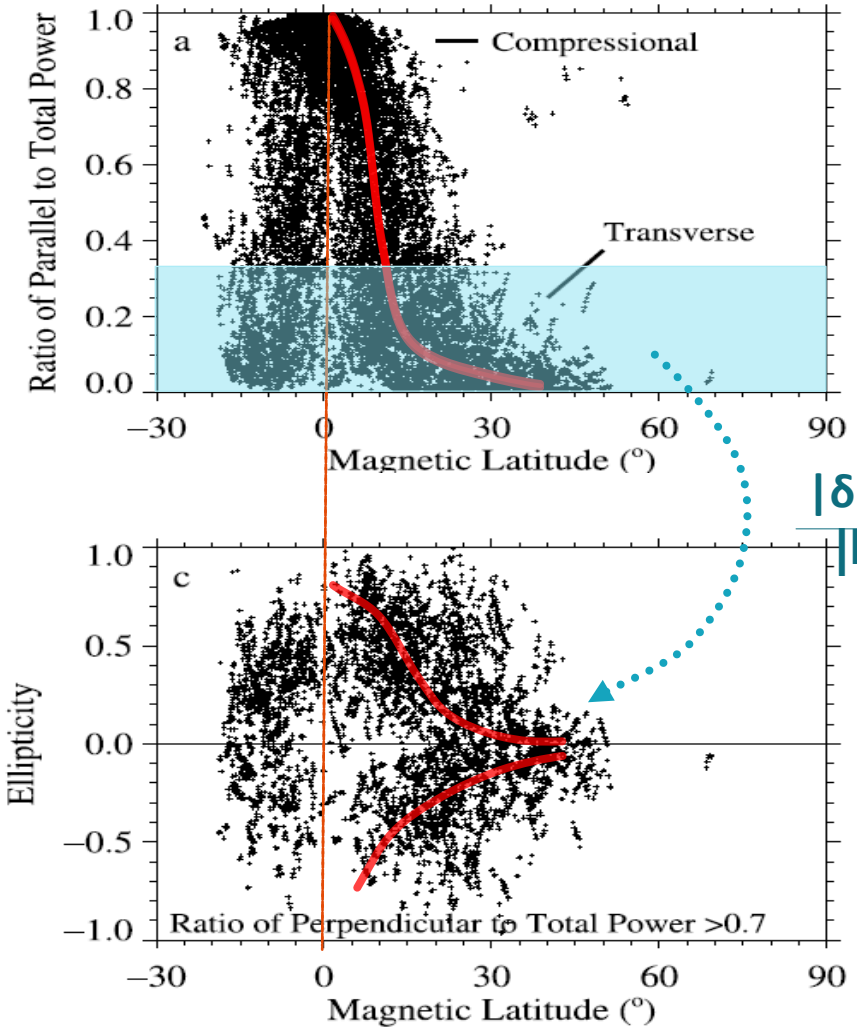
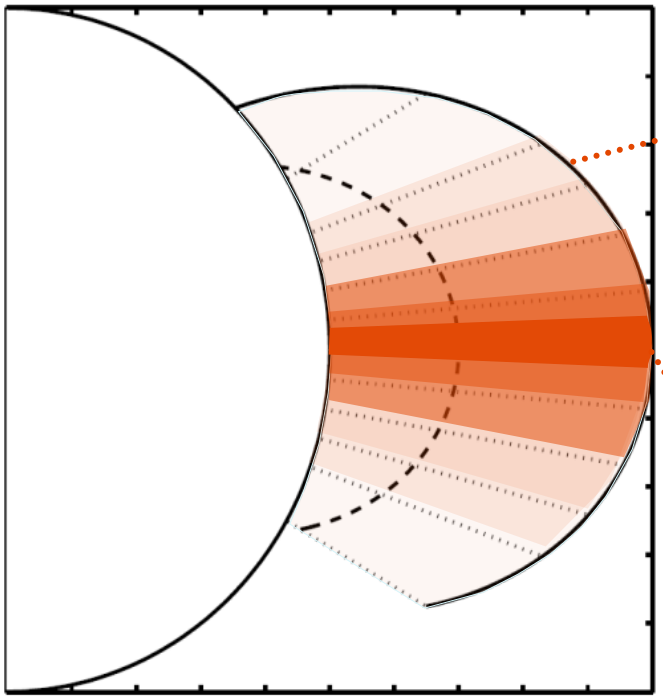


$$\frac{|\delta b_\perp|^2}{|b|^2} > 0.7$$

Boardsen et al., 2012

Summary
: Wave Characteristics



off Equator

Weak occurrence

Transverse and Linear

Equator

High occurrence

Compression and Harmonic

Ion-ion hybrid resonance

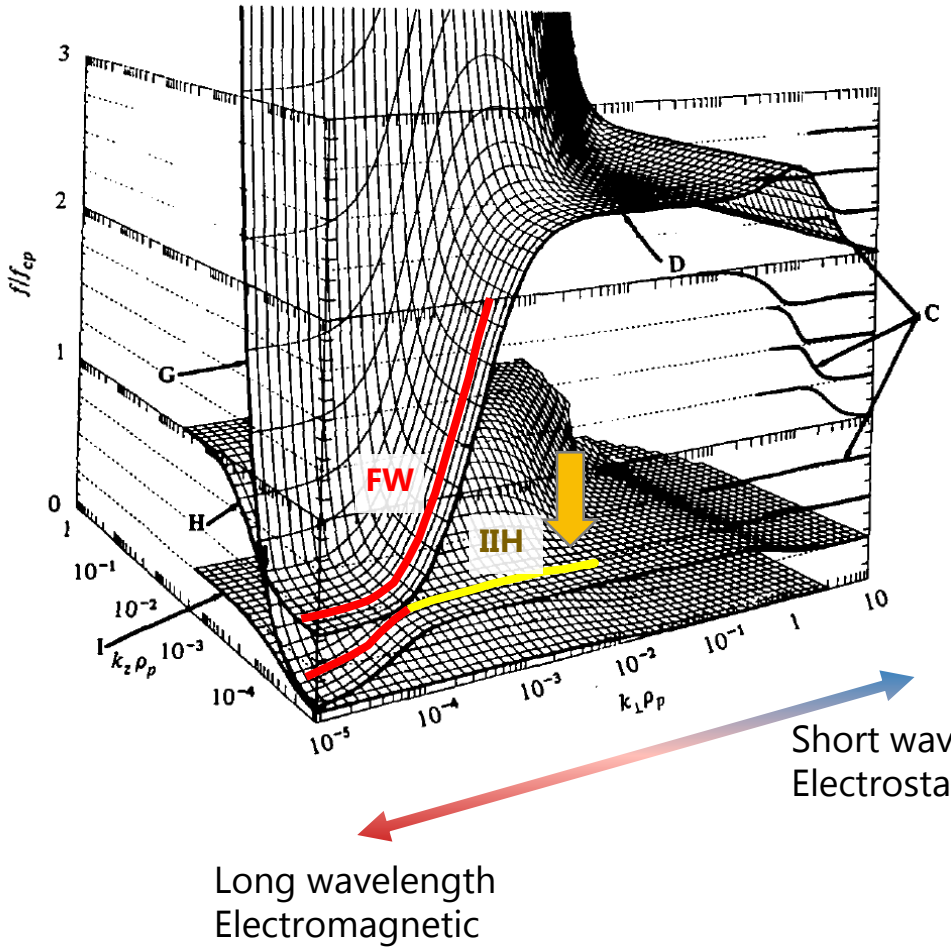
FW : Fast compressional wave
IIH : Mode-converted Ion-ion hybrid resonant wave

between two ion gyrofrequencies

+ Fast compressional waves are converted to "ion-ion hybrid resonance"

+ Mode converted ion-ion hybrid resonance
  - Field-aligned propagation
  - Long wavelength in field-aligned direction
  - kperp >> $k_{||}$
  - Transverse waves
  - Linear polarization

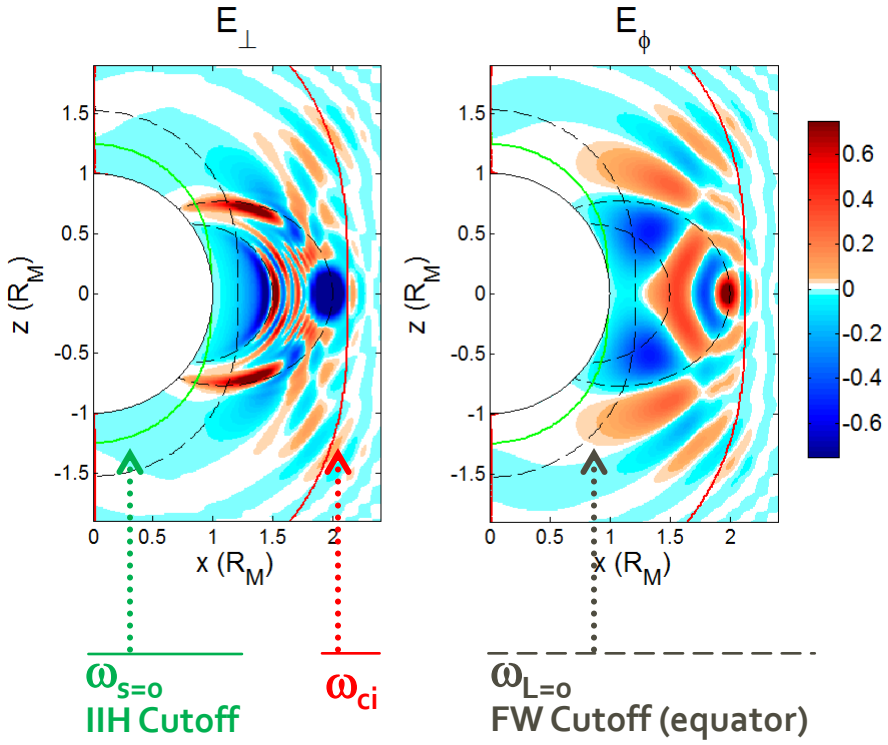
➔ **2D Full wave calculations has been performed in Mercury's magnetosphere**



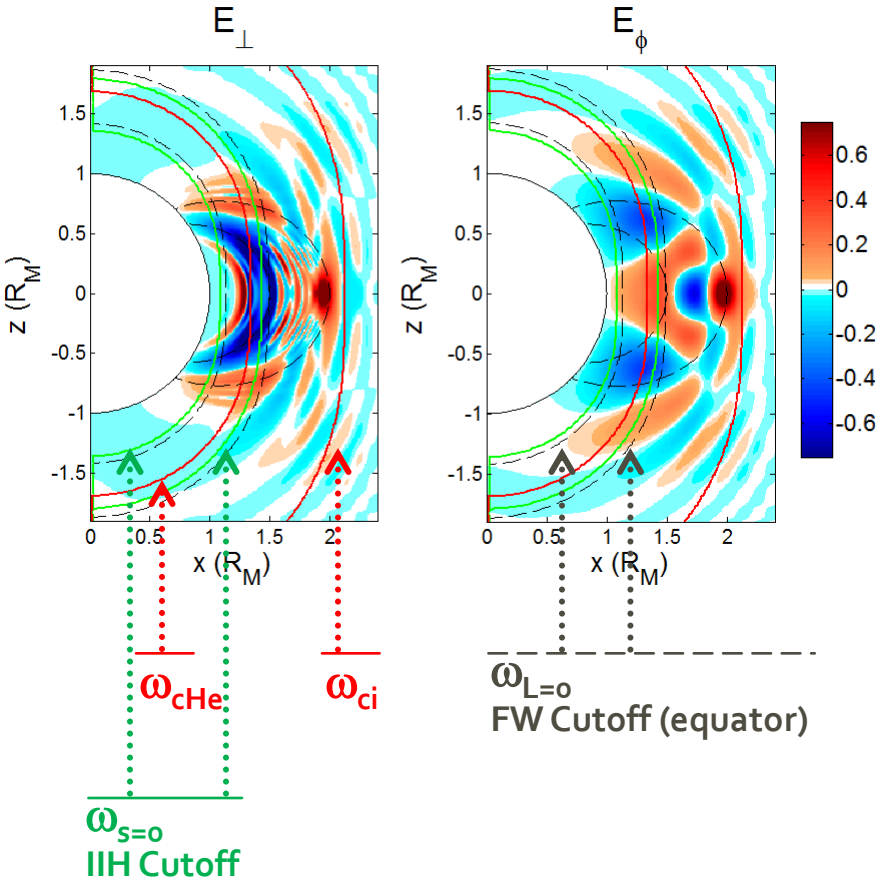
Full wave calculations (cold)

+ $B_{0\ (surface)}$: 3 X 10^{-7} T
+ N_e : 3 /cm^3
+ f = 0.8 f_{ci} at L=2 (equator)

H^+ 85% Na^+ 15%



H^+ 85% He^+ 7.5% Na^+ 7.5%



Kim et al., 2015a, submitted to Geophys. Res. Lett.

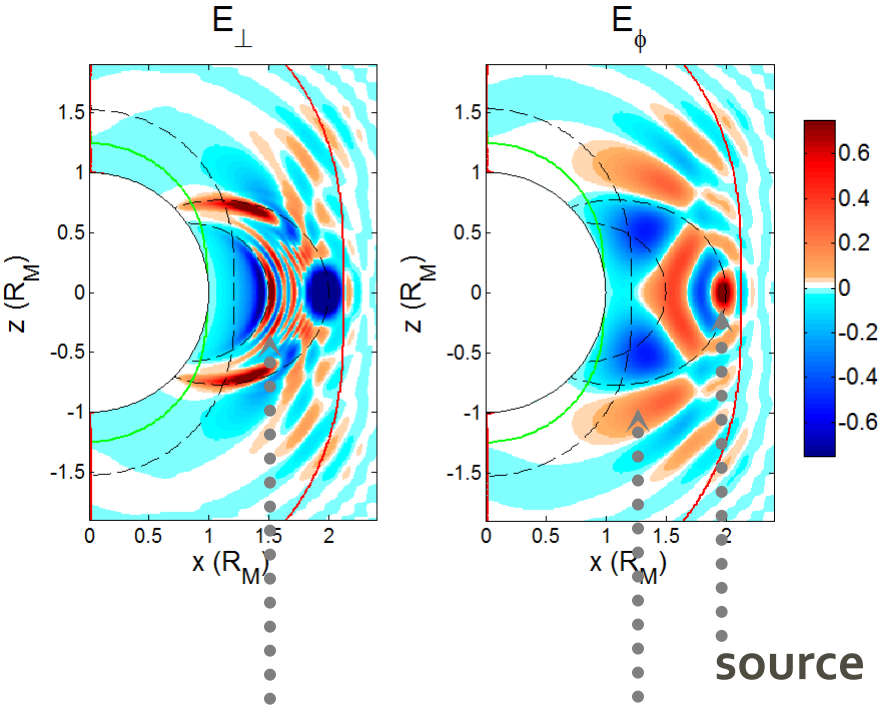
Full wave calculations

ω_{ci} or ω_{cHe}

$\omega_{s=o}$ IIH Cutoff

$\omega_{L=o}$ FW Cutoff (equator)

H^+ 85% Na^+ 15%



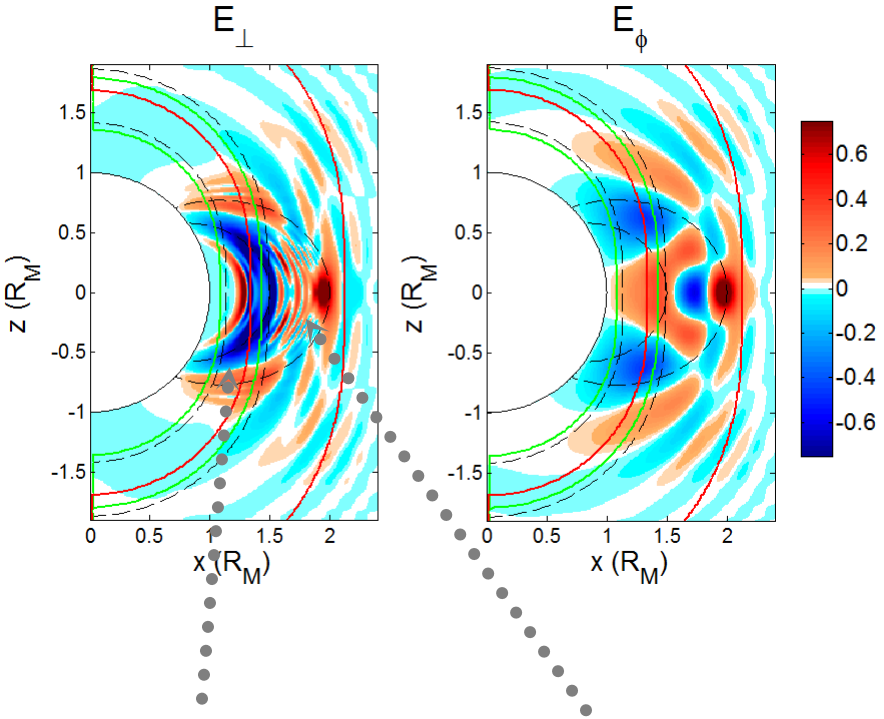
source

FW

Ion-ion hybrid resonance

$\omega_{cNa} < \omega < \omega_{ci}$

H^+ 85% He^+ 7.5% Na^+ 7.5%



IIH resonance

$\omega_{cNa} < \omega < \omega_{cHe}$

IIH resonance

$\omega_{cHe} < \omega < \omega_{ci}$

Kim et al., 2015a, submitted to Geophys. Res. Lett.

Full wave calculations

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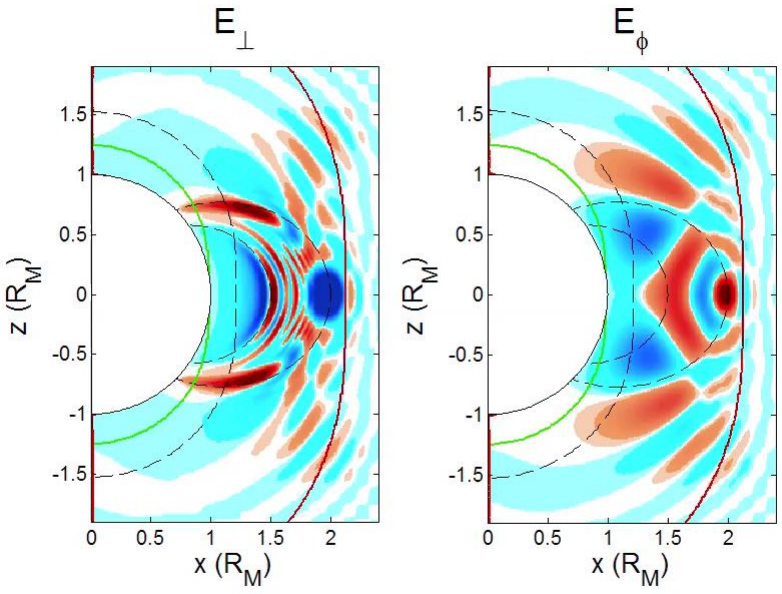

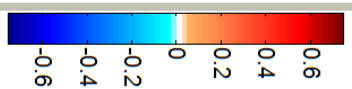

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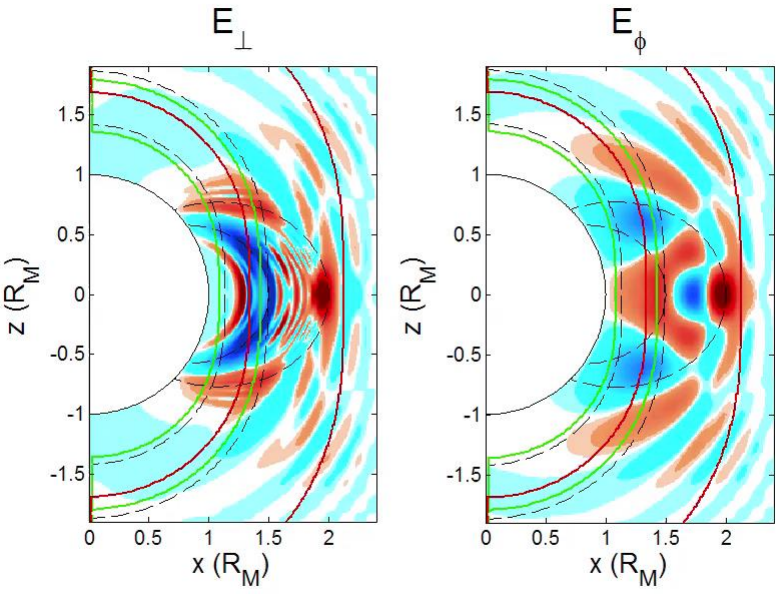
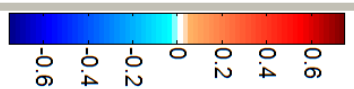
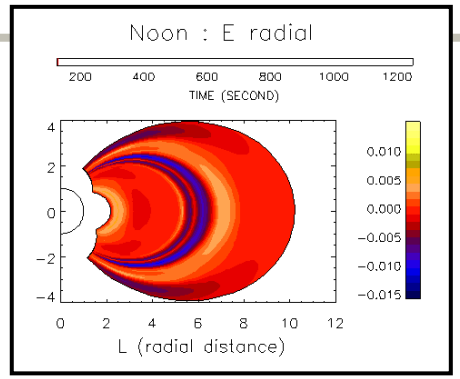


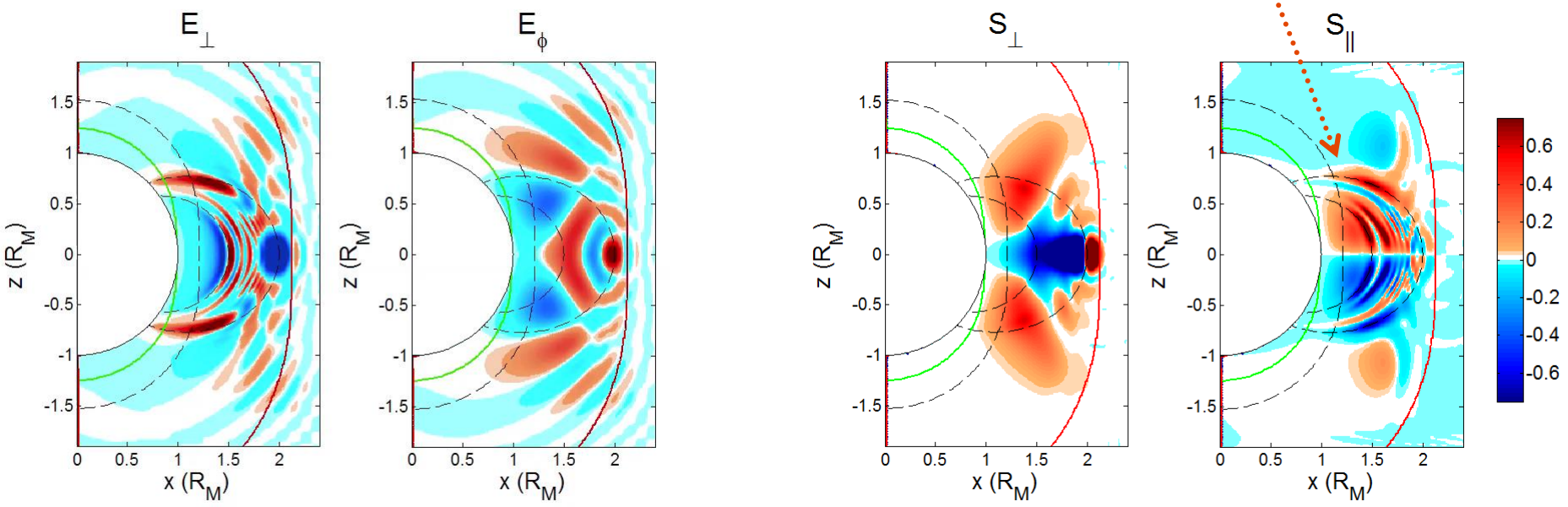




Poynting Flux

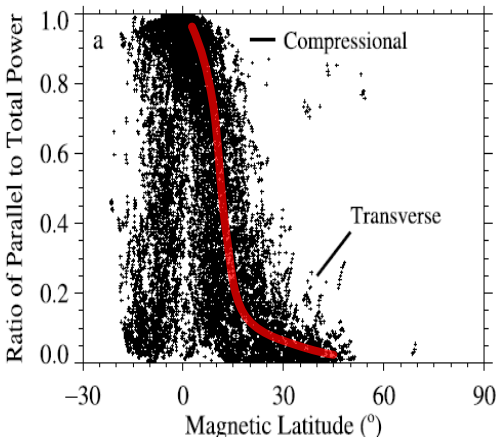
Guided by Magnetic field!

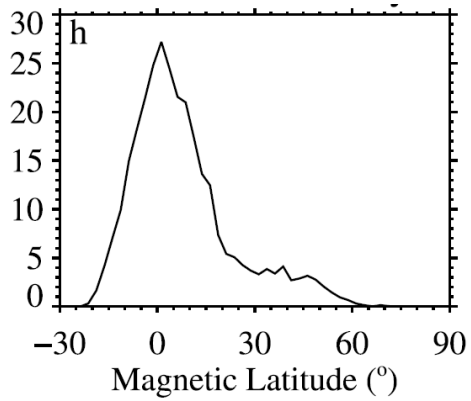
H^+ 85% Na^+ 15%



Kim et al., 2015a, submitted to Geophys. Res. Lett.

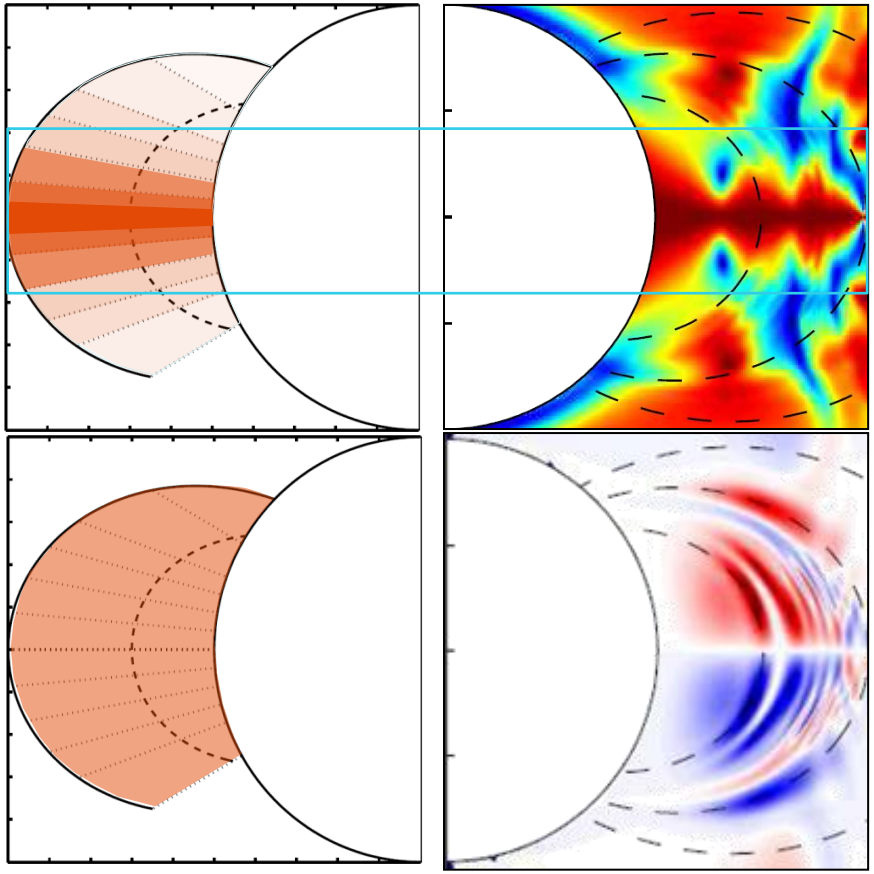
Comparison with observation





Observation

Full wave calculation



Compressibility

Equator - high
Off Equator - low

Latitude coverage

cf. Ion Bernstein Waves : Ray Tracing

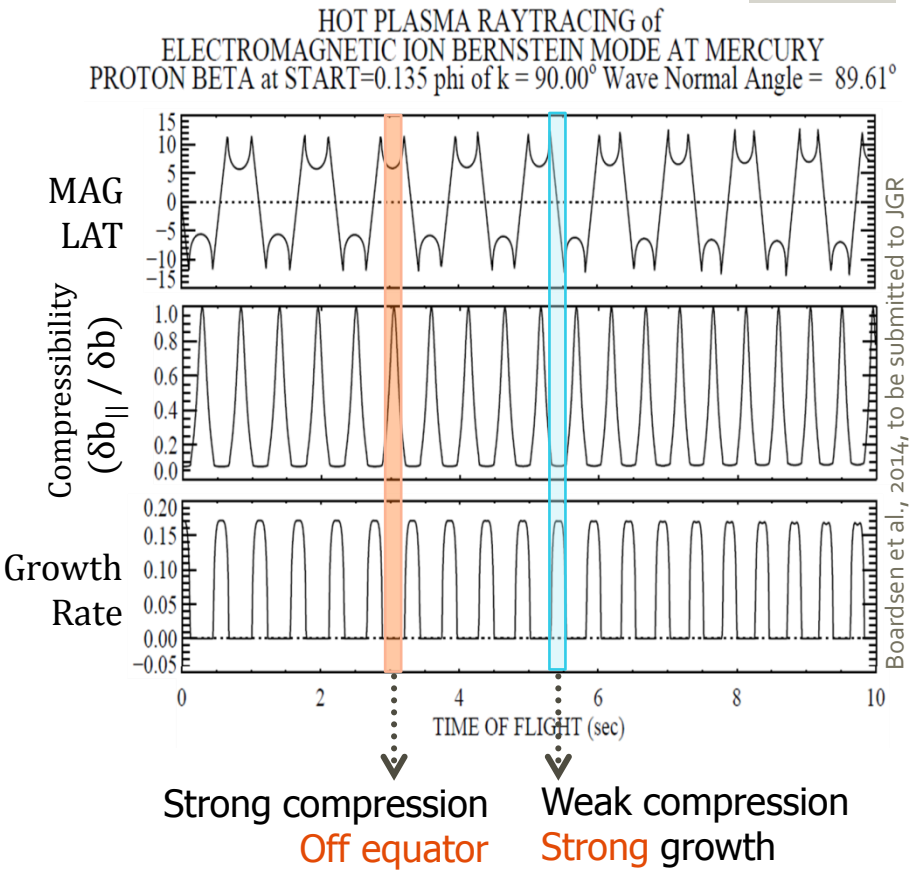
β = 0.135

+ **Ray tracing**
- bi-modal structure
- Weak compression and strong growth near equator
- Highly compression near |4° - 7°|

+ **β = 0.051**
- also shows only Type A

It could explain MESSENGER because it occurs in various beta range.

Type A



Boardsen et al., 2014, submitted to J. Geophys. Res.

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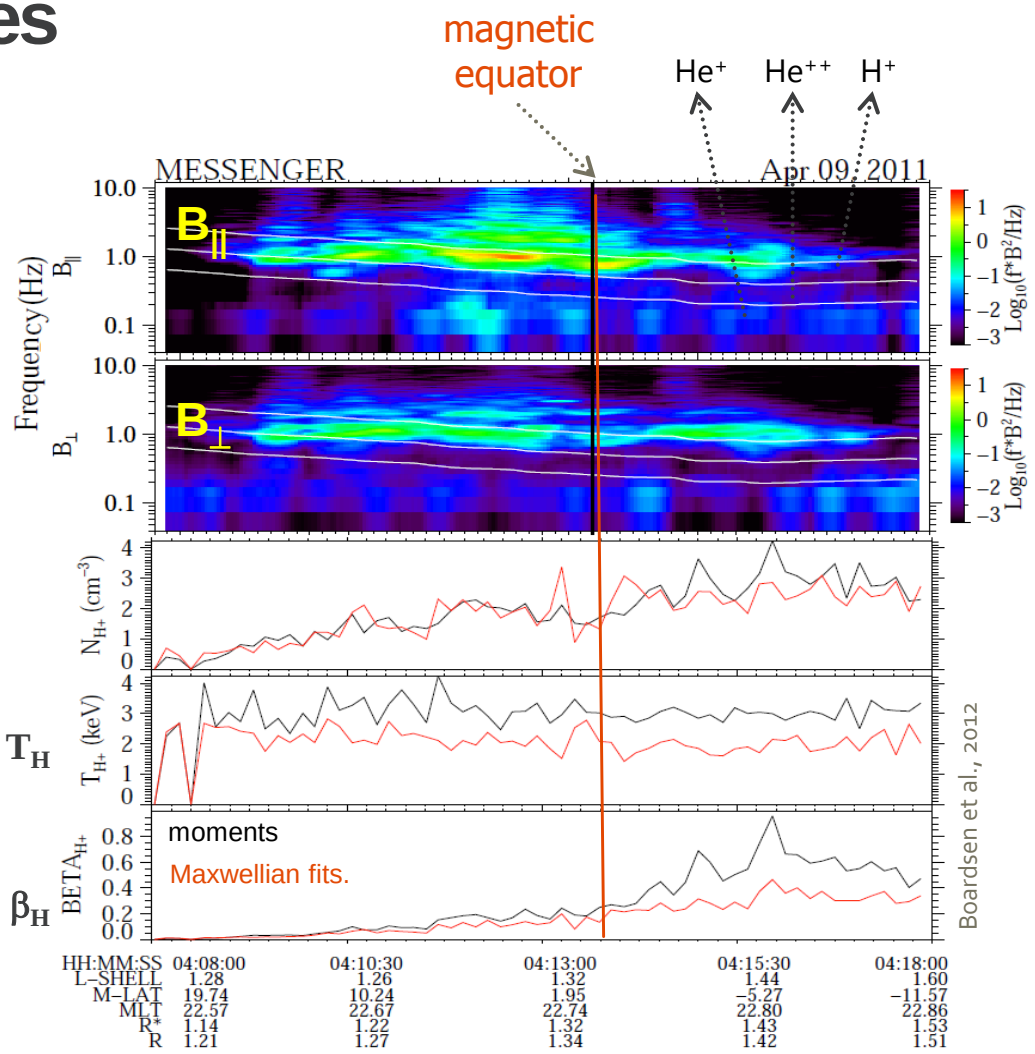
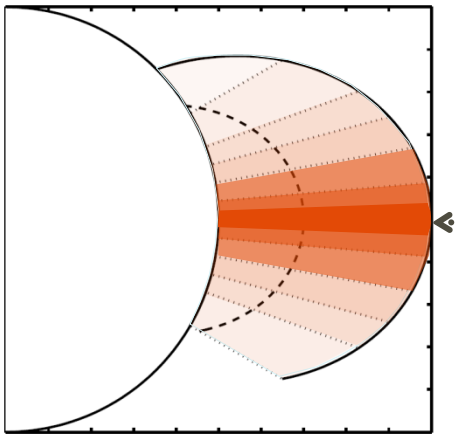


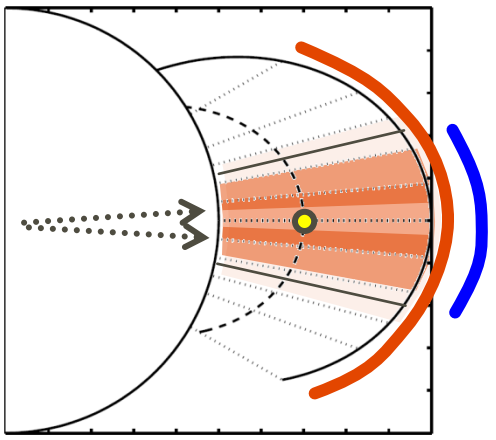
cf. Ion Bernstein Waves
: Comparison with observation

Observation



Highly
Compression
near Equator

Ray tracing



Observation

Ray Tracing

Comparison

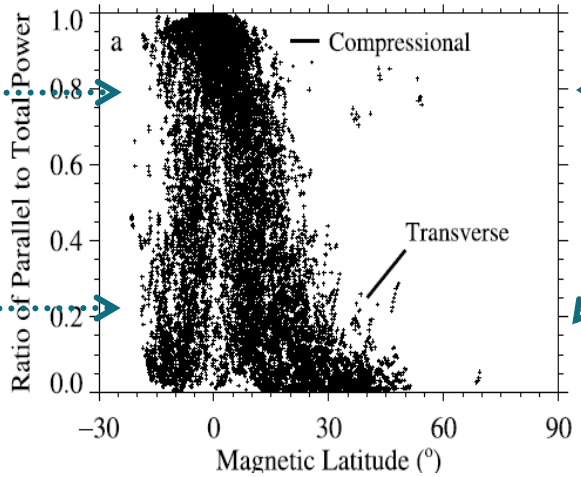
Full wave calculations

Compressional Wave power ?

Long-wave length Mode-converted waves

COLD plasma

Observation



IBW ray tracing

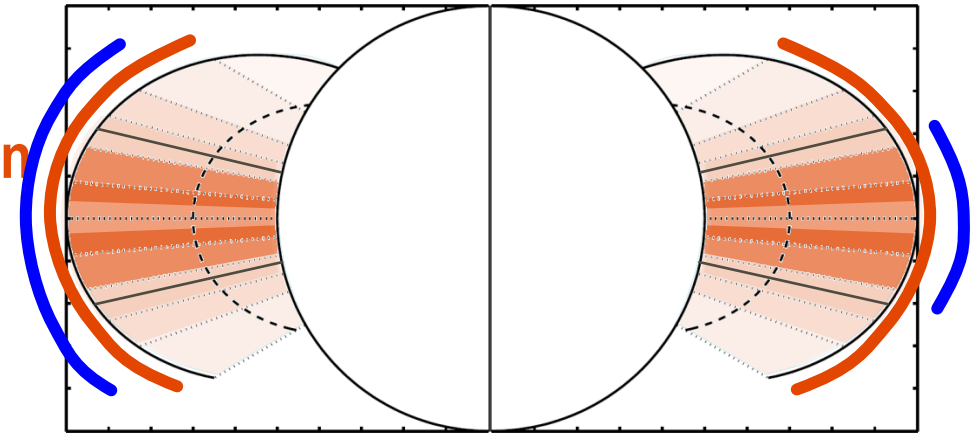
Ion Bernstein waves

Doppler Shift

Observation

≀

FLR



Observation

﹀

Ray Tracing

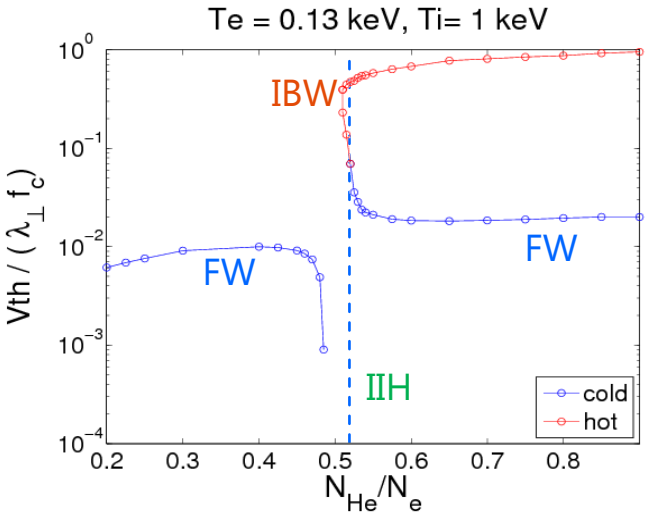
Mode Conversion in hot plasma

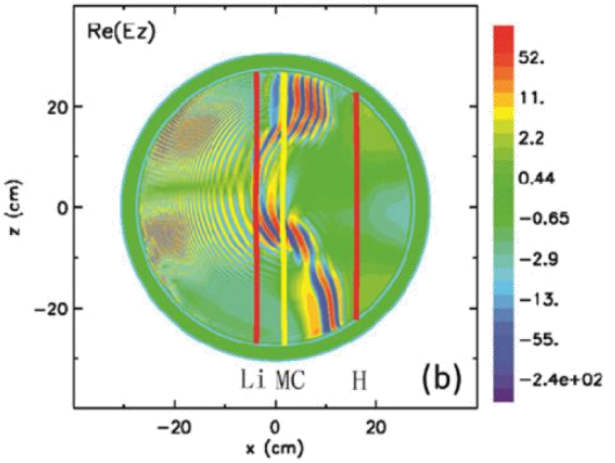
FW : Fast compressional wave
IIH : Mode-converted ion-ion hybrid resonant wave
IBW : Ion Bernstein waves

Dispersion relation at Mercury

+ using WHAMP
+ Parameters
  - B_0 = 90 nT
  - N_e = 3 cm^{-3}
  - $K_{||}$ = $2\pi/(1.5R_M)$
  - $T_\perp/T_{||}$ =1
  - T_{ion}=1 keV
  - T_e = 0.13 keV
  - ω = 0.7 ω_{ci}
  - No cold plasma

+ At Mercury's hot plasmas, mode conversion from fast compressional waves to ion-Bernstein waves occurs at the ion-ion hybrid resonance
← Similar to laboratory plasma





Zhang et al., 2012

PART 2 : EARTH'S MAGNETOSPHERE

Linear Polarization
EMIC waves
& IIH resonance

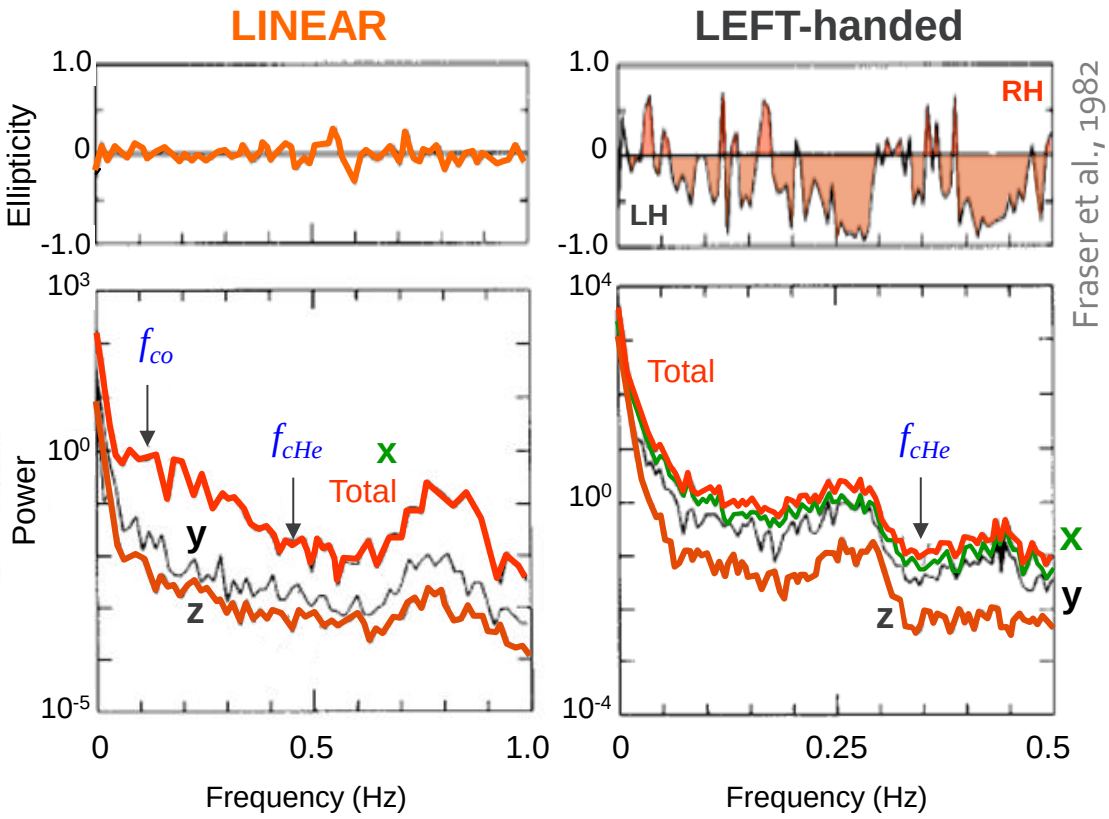
EMIC waves at Earth

Left-handed Polarization

+ Ion cyclotron instability by proton temperature anisotropic

Linear Polarization

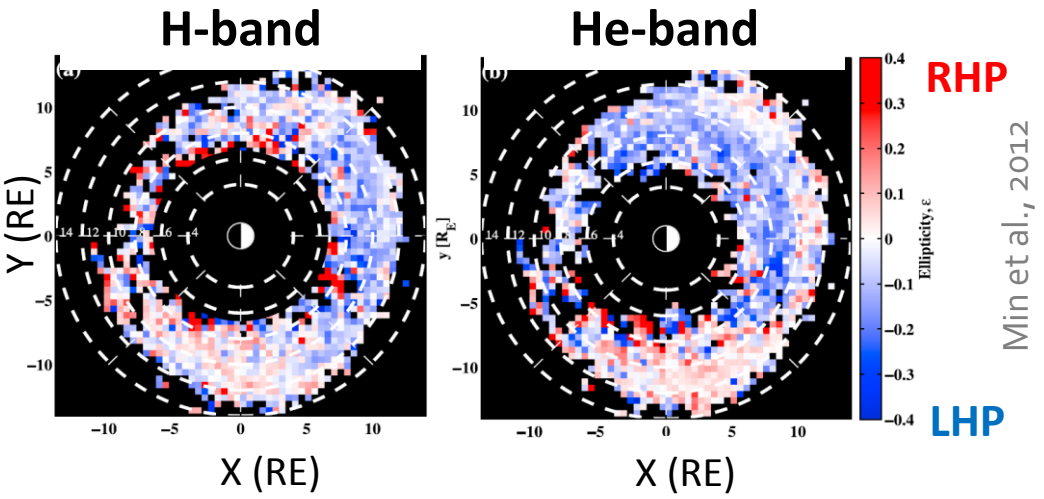
+ mode conversion at the IIH resonance [Lee et al., 2008]



EMIC waves at Earth

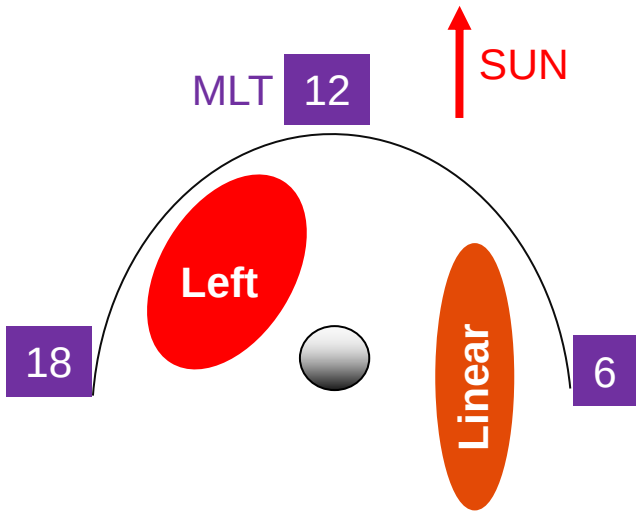
Linear Polarization

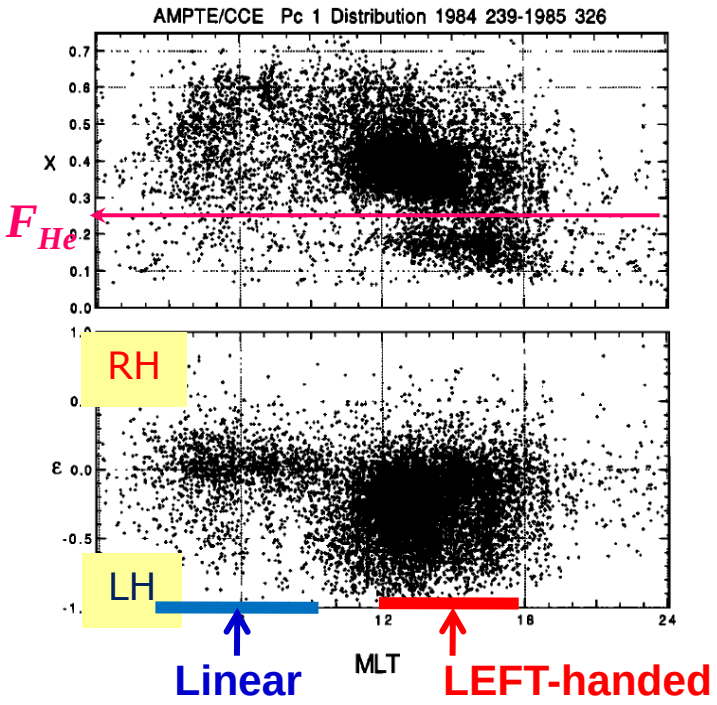
+ Linearly Polarized EMIC waves are observed in a wide range of L-shell



Min et al., 2012

Issue:
How linear polarization is dominant?
How such EMIC waves can be generated?

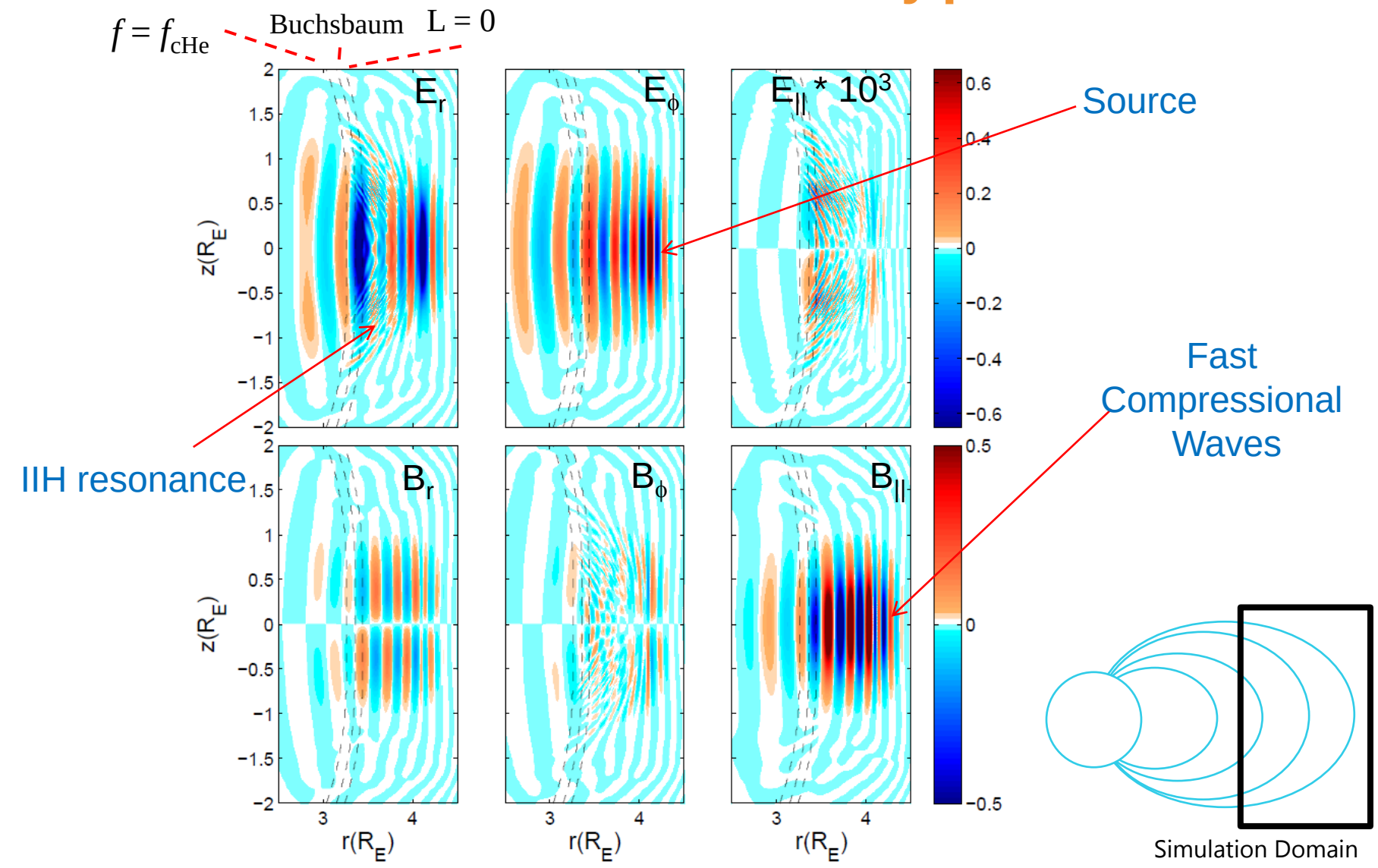




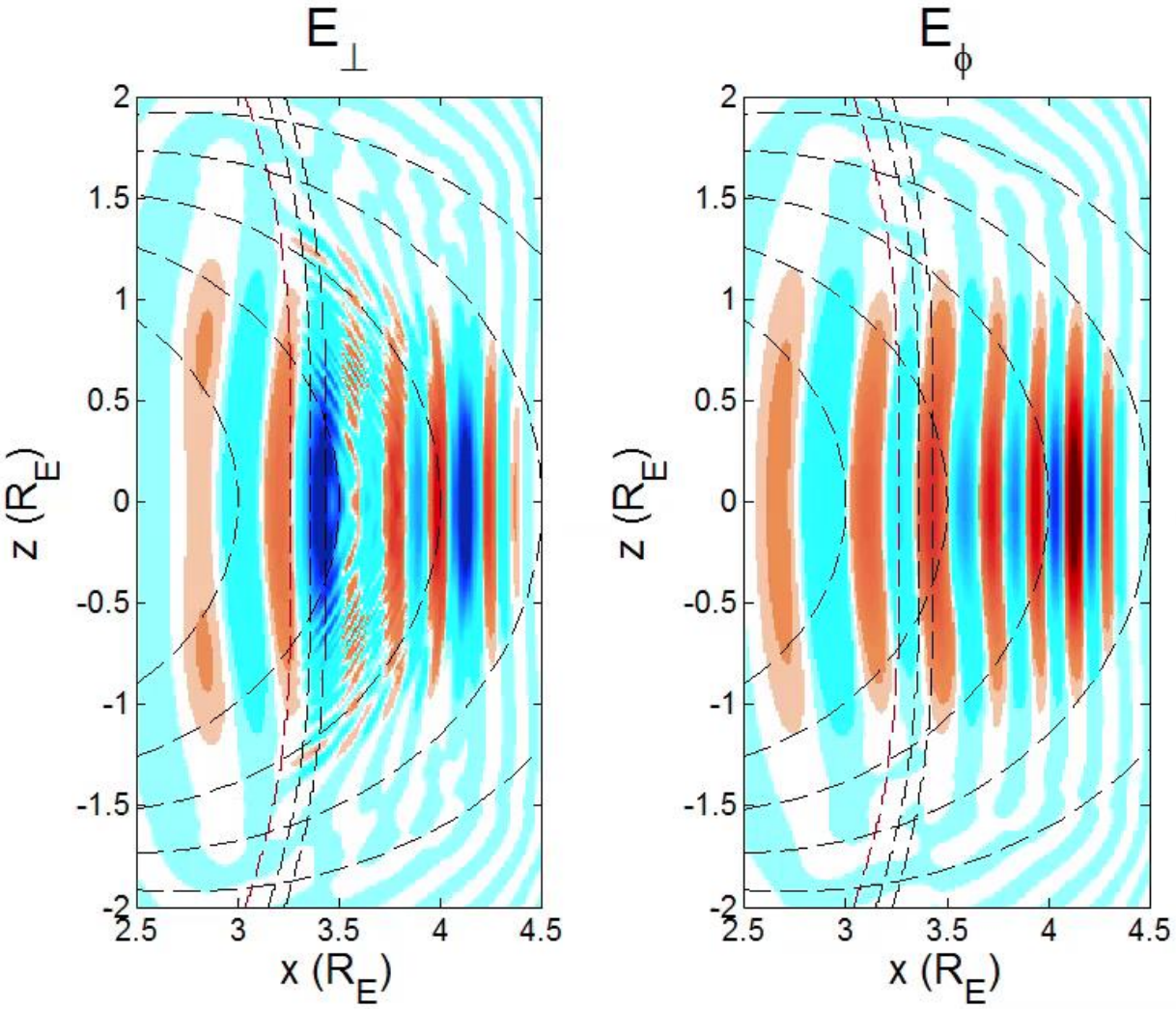
Anderson et al., 1992

Full wave calculations at Earth

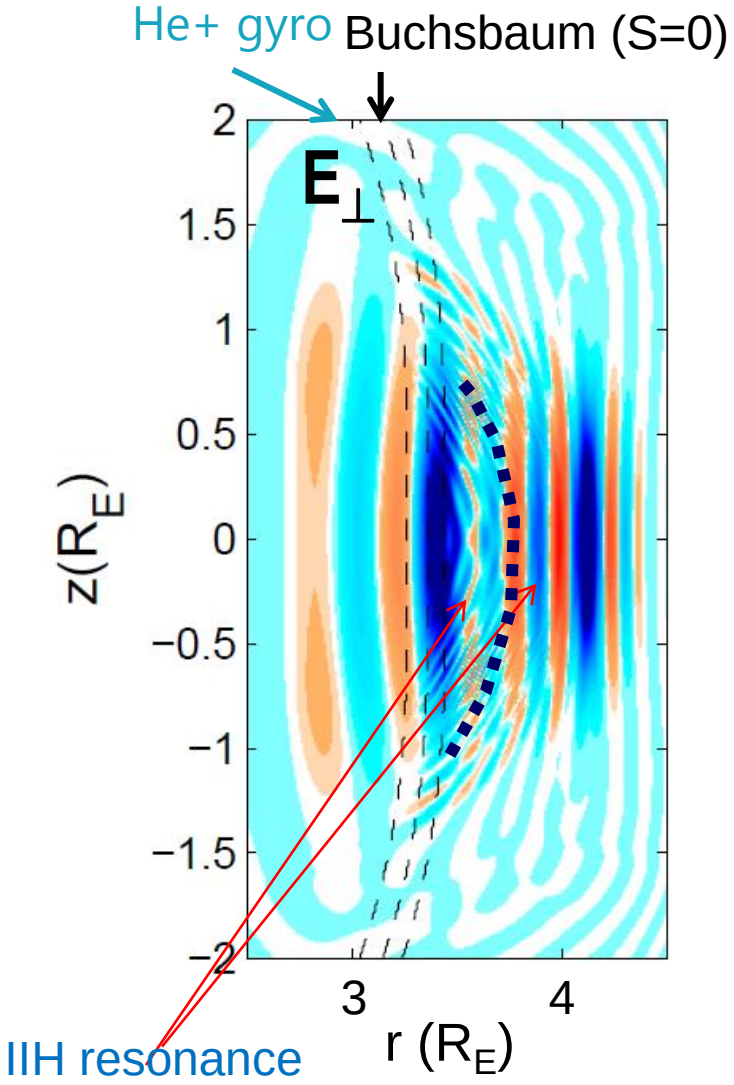
: Mode converted waves → linearly polarization



Mode converted waves → linearly polarization



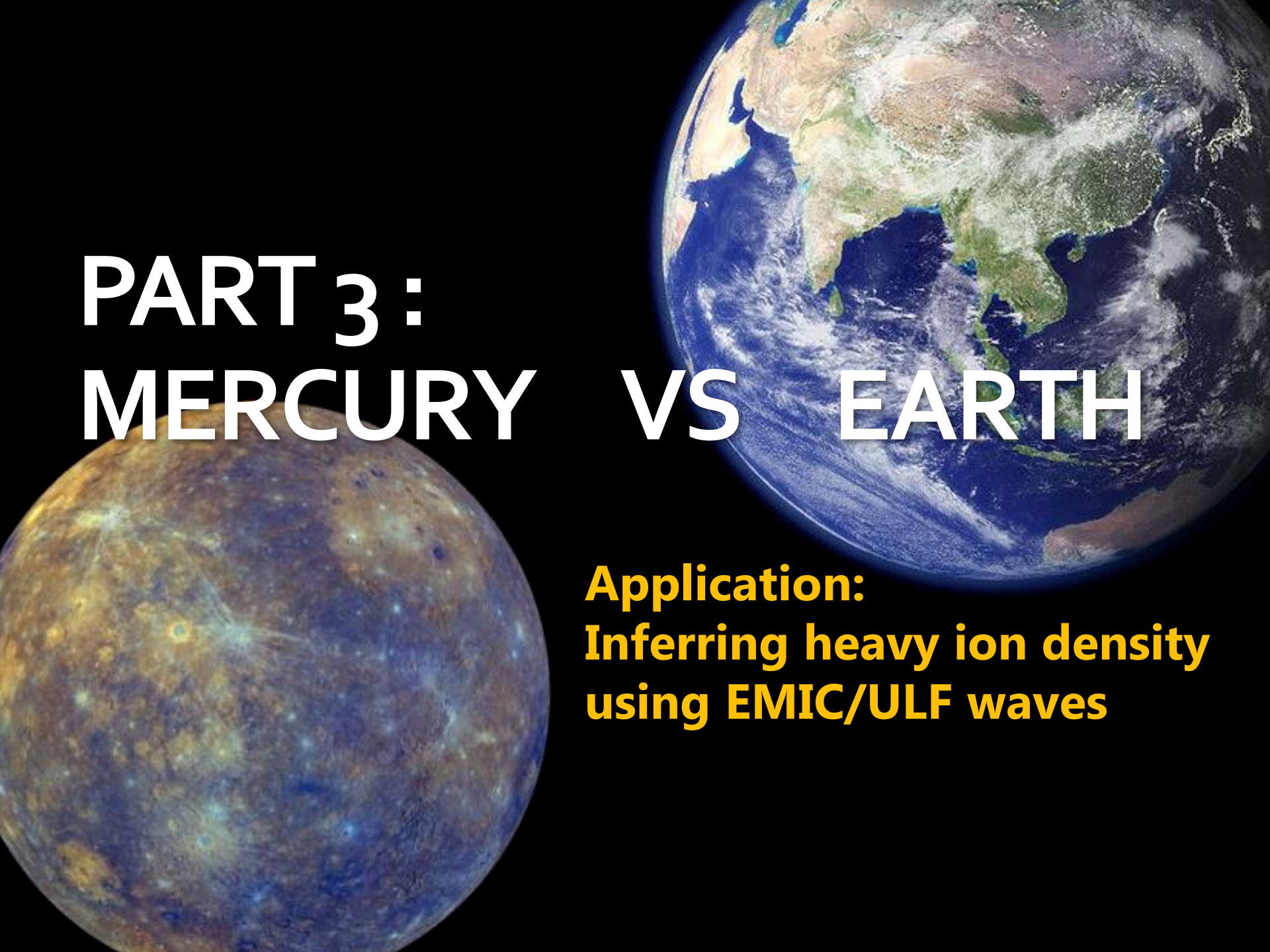
Mode converted waves → linearly polarization → localized



- $f_{He+} < f < f_{H+}$
- Wave Dispersion
  $n_{||}^2 = S$
- Cut offs occur at S = 0 (Buchsbaum resonance)
- IIH resonances are localized between two Buchsbaum resonances

[e.g., Johnson et al.,

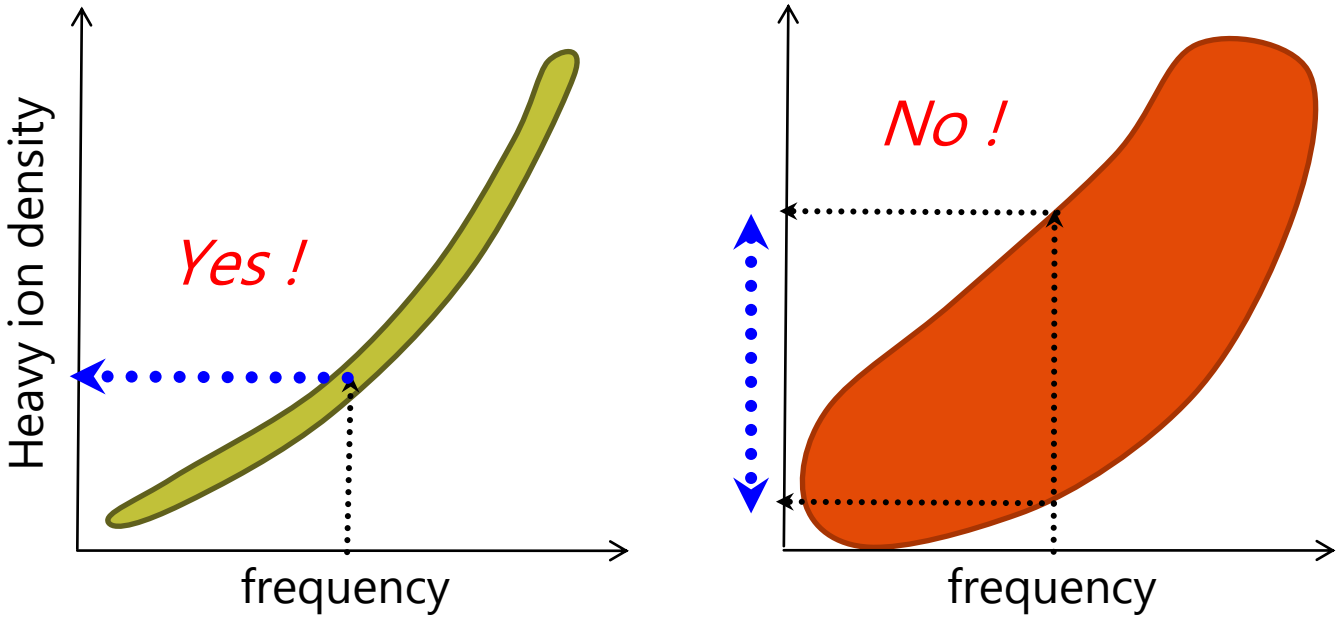
PART 3 : MERCURY VS EARTH



Application:
Inferring heavy ion density using EMIC/ULF waves

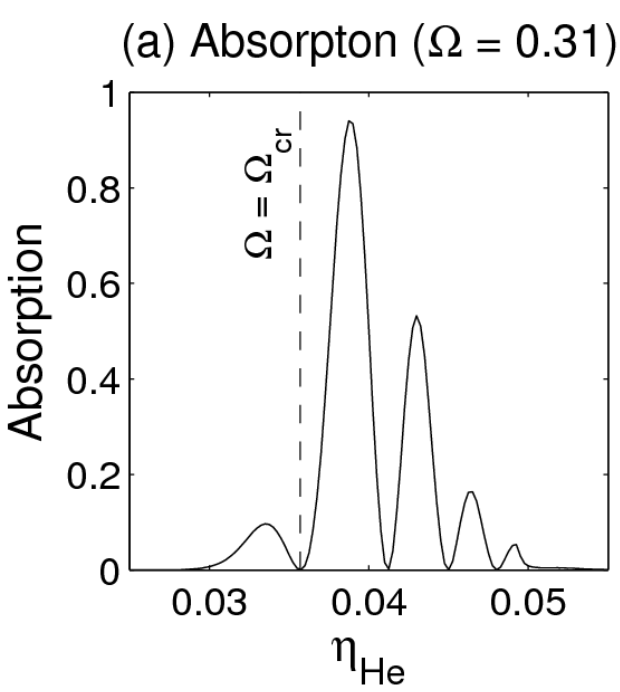
Can detected ULF waves be a diagnostic tool to estimate heavy ion density ratio?

Absorption of fast compressional waves
= Generation of linear polarization waves

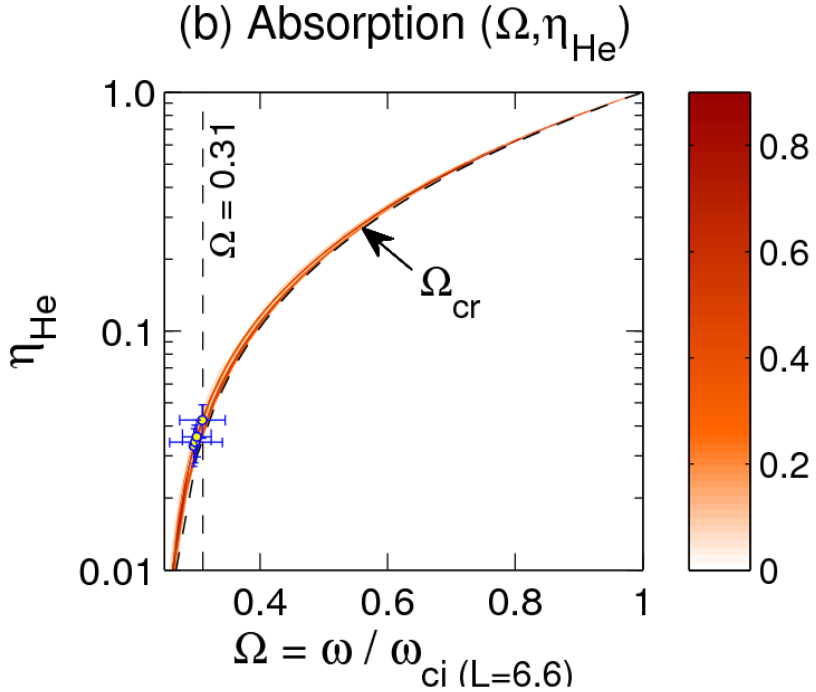


Key point : *width*

Wave absorption at Earth : adopting simple density model



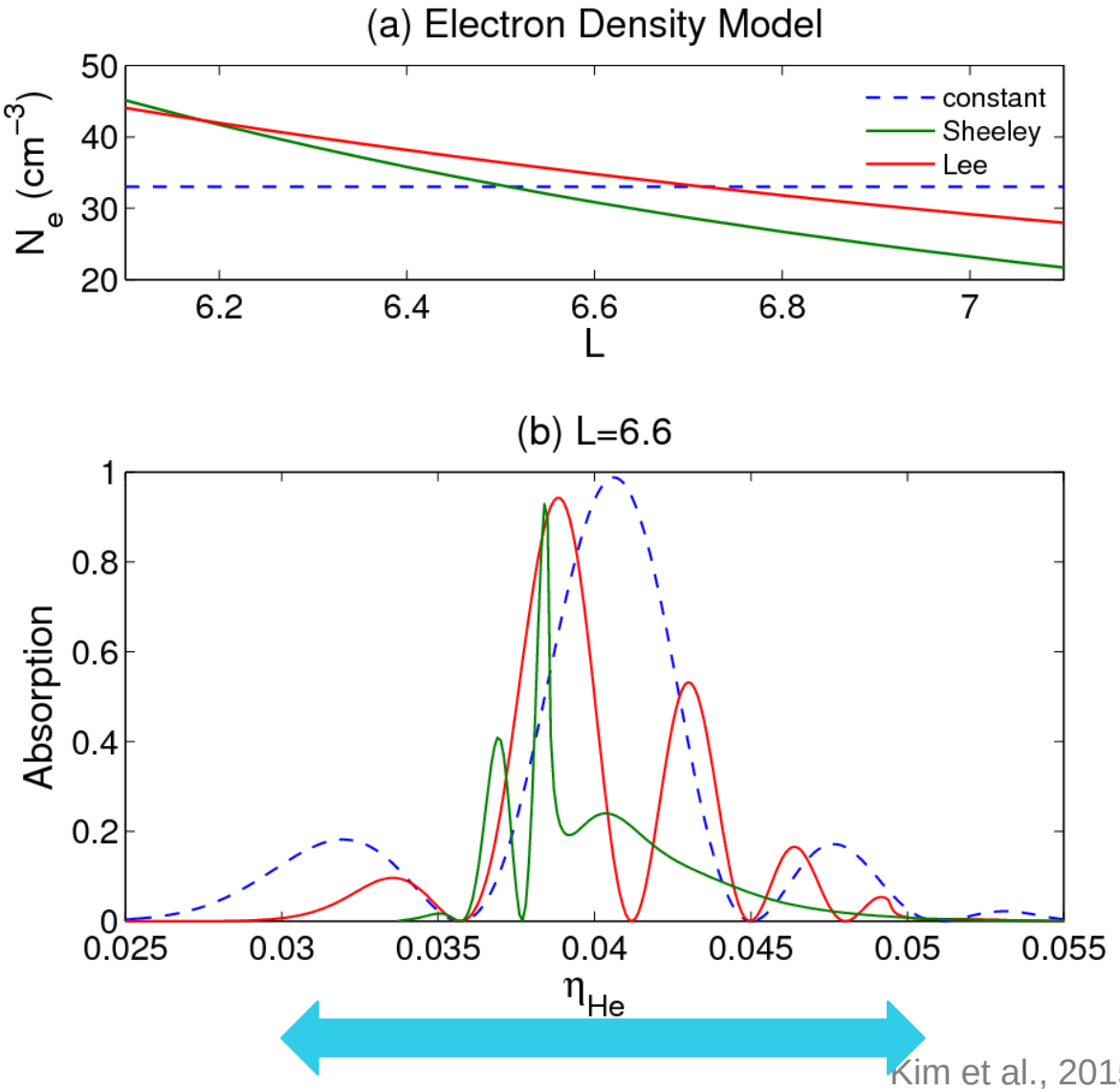
$\Delta\eta_{He}$ ~ 2%



IIH resonance frequency
~ crossover frequency

Kim et al., 2015b, submitted to J. Geophys. Res.

Wave absorption at Earth : adopting *various* density model

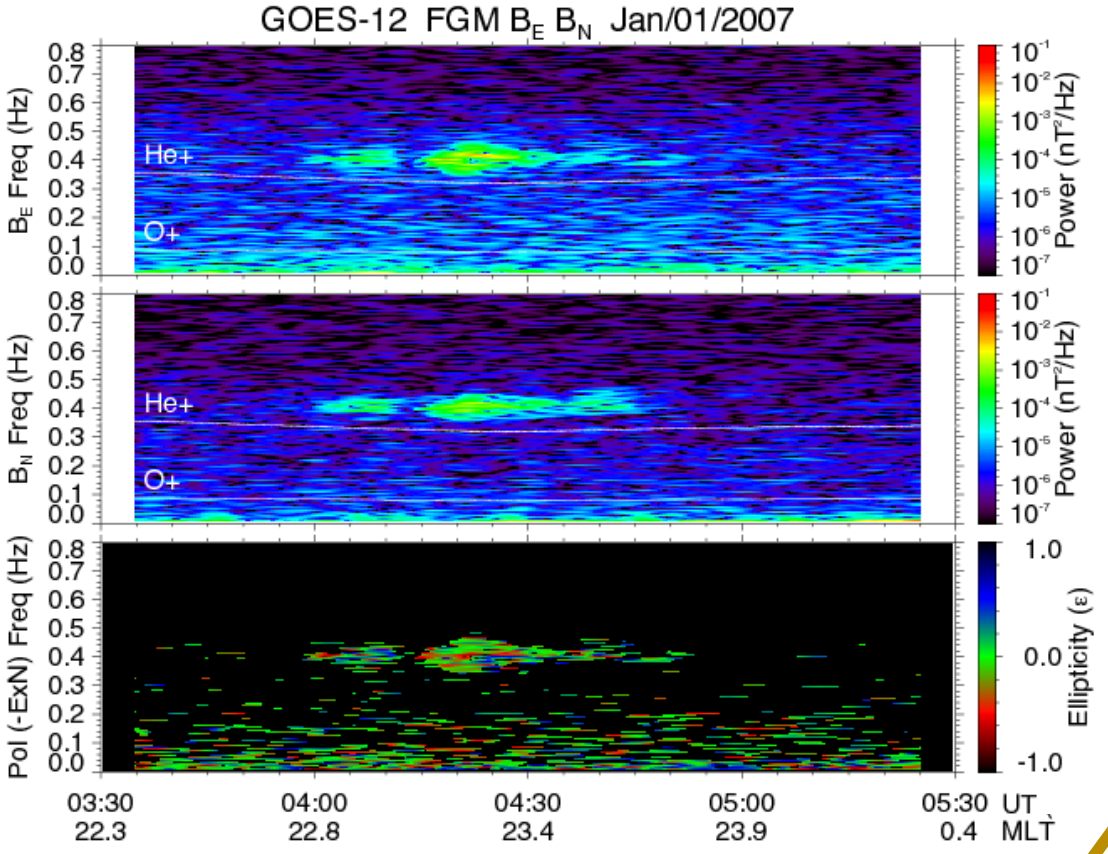


$\Delta\eta_{He}$: not sensitive to the radial structure of electron density profile

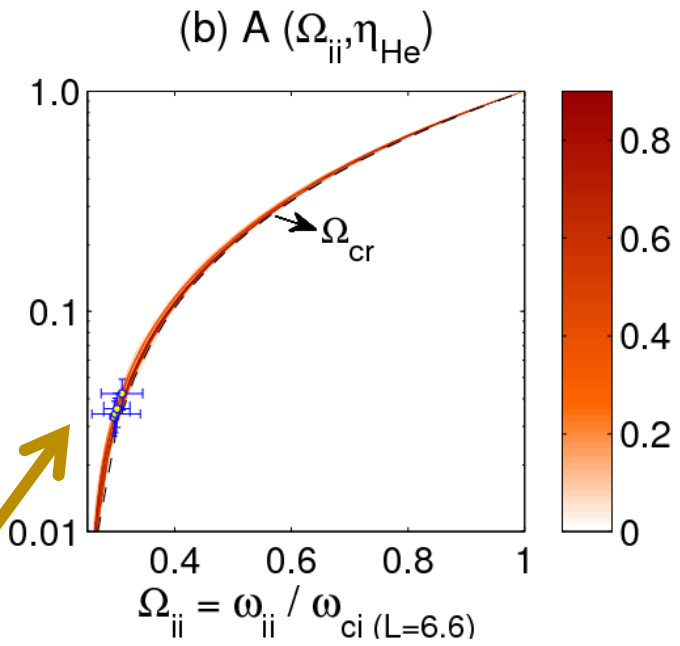
→ η_{He} can be inferred from the observed EMIC waves at geosynchronous orbit, which is robust for typical magnetospheric parameters.

Kim et al., 2015b, submitted to J. Geophys. Res.

Heavy Ion Density Estimation at Earth : Geosynchronous orbit L ~ 6.6

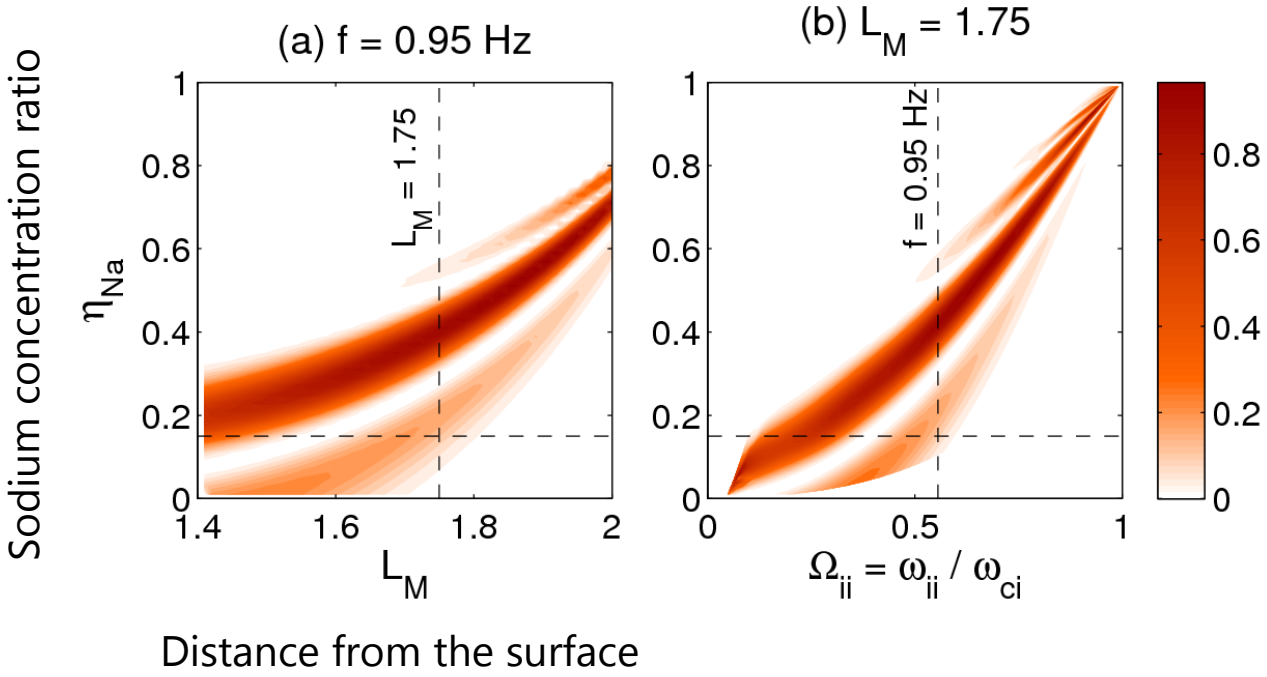


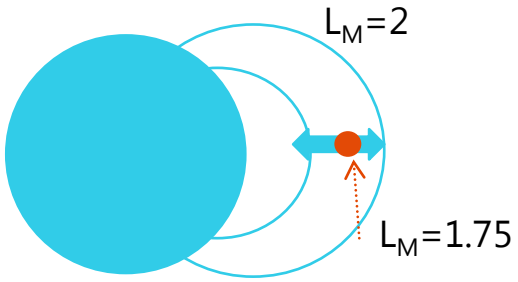
f ~ 0.35 – 0.45 Hz
f / fci ~ 0.28 – 0.29



He+ density ratio : 3.3 – 4.2 ± 0.7 %

Wave absorption at Mercury : adopting simple density model

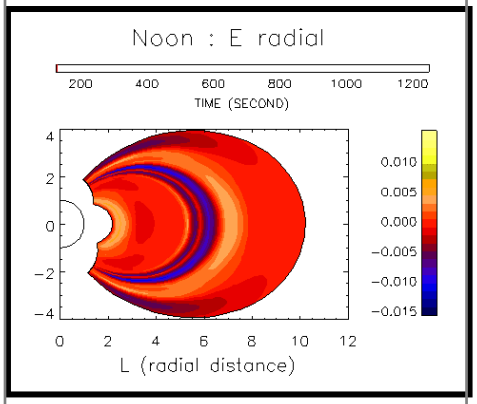
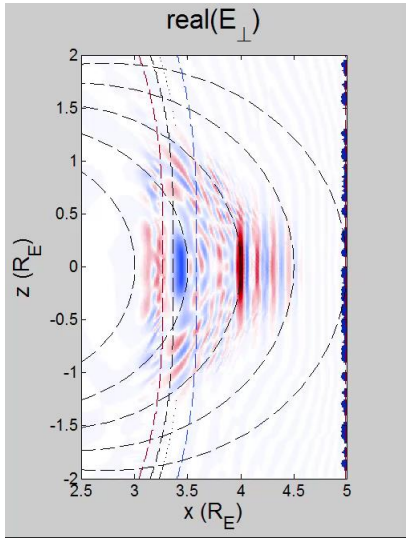
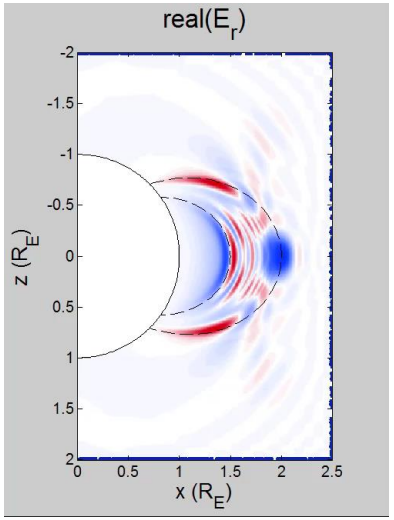
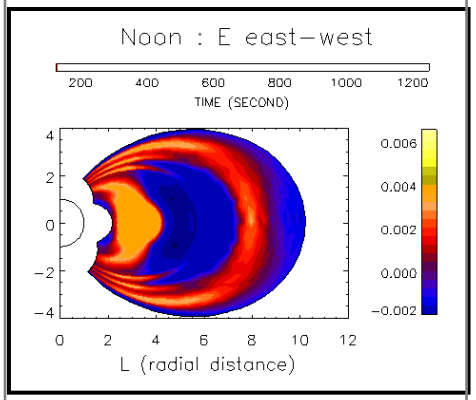
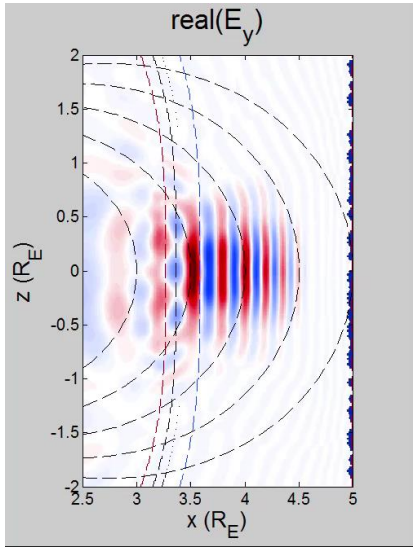
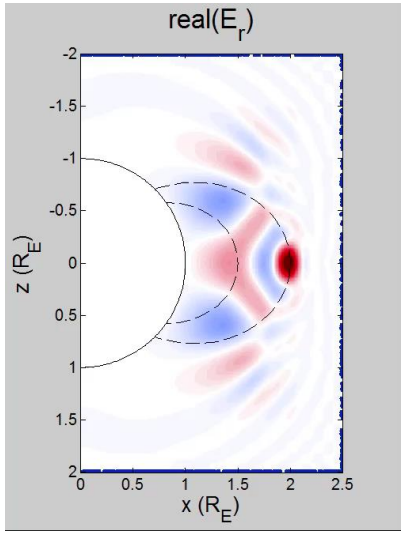


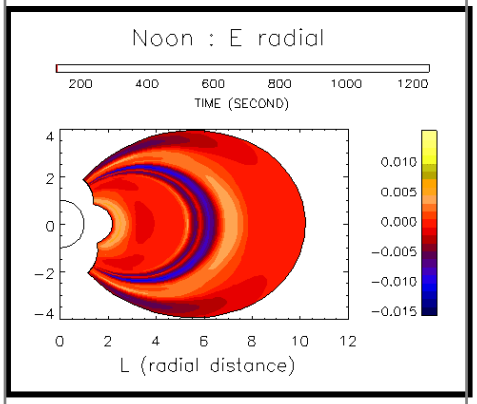
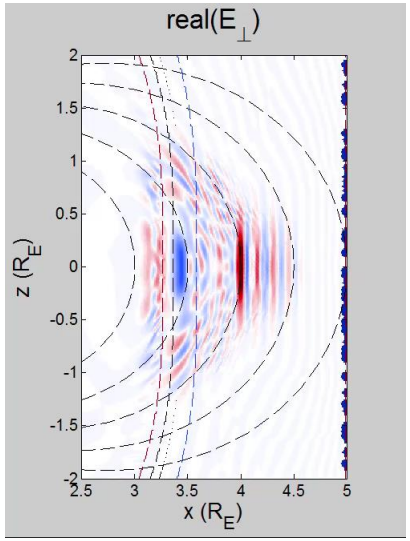
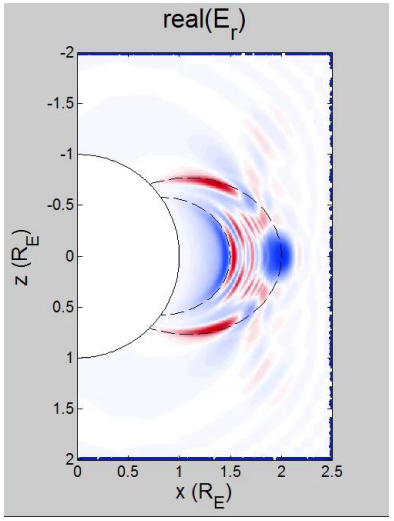
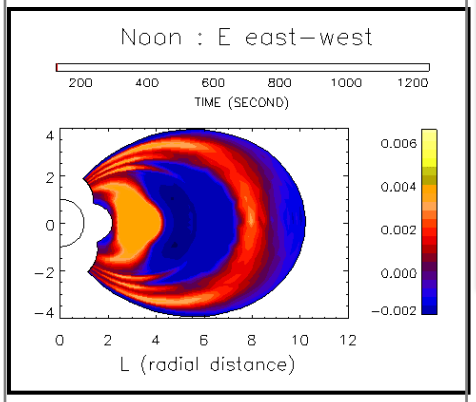
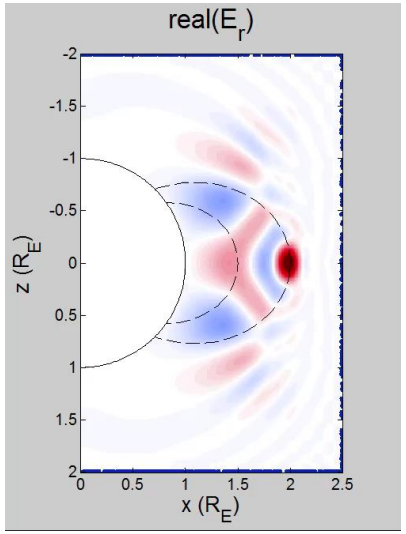


$\Delta\eta_{Na}$ ~ 40% !

η_{ion} can **NOT** be simply inferred from the observed ULF waves at Mercury

Kim et al., 2015c, submitted to “Low-frequency waves in space plasmas”, AGU monograph

	FLR resonance at Earth (Alfven resonance : global)	EMIC waves at Earth (IIH resonance : localized)	FLR at Mercury (IIH resonance : global)
Mode converted waves at the IIH or Alfven resonance Field-aligned Propagation Linear Polarization			
Fast compressional mode (externally driven incoming waves)			

	FLR resonance at Earth (Alfven resonance : global)	EMIC waves at Earth (IIH resonance : localized)	FLR at Mercury (IIH resonance : global)
Mode converted waves at the IIH or Alfven resonance Field-aligned Propagation Linear Polarization			
Fast compressional mode (externally driven incoming waves)		Inferring Heavy Ion Density!	

END

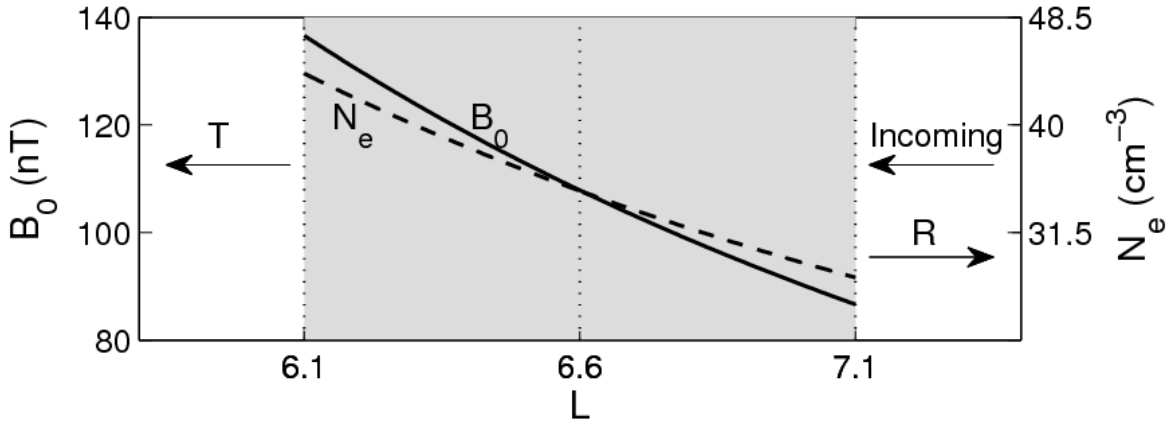
Observed linear polarized EMIC waves (IIH resonance) can be used to infer the heavy ion density.

Fast mode absorption at the IIH resonance depends on wave frequency ω, azimuthal (k_y), field-aligned wave numbers ($k_{||}$) , heavy ion density ratio, and $\mathbf{B}_0$.

→ IIH resonance has been suggested to estimate heavy ion density [Kim et al., 2008, Lee et al., 2008]

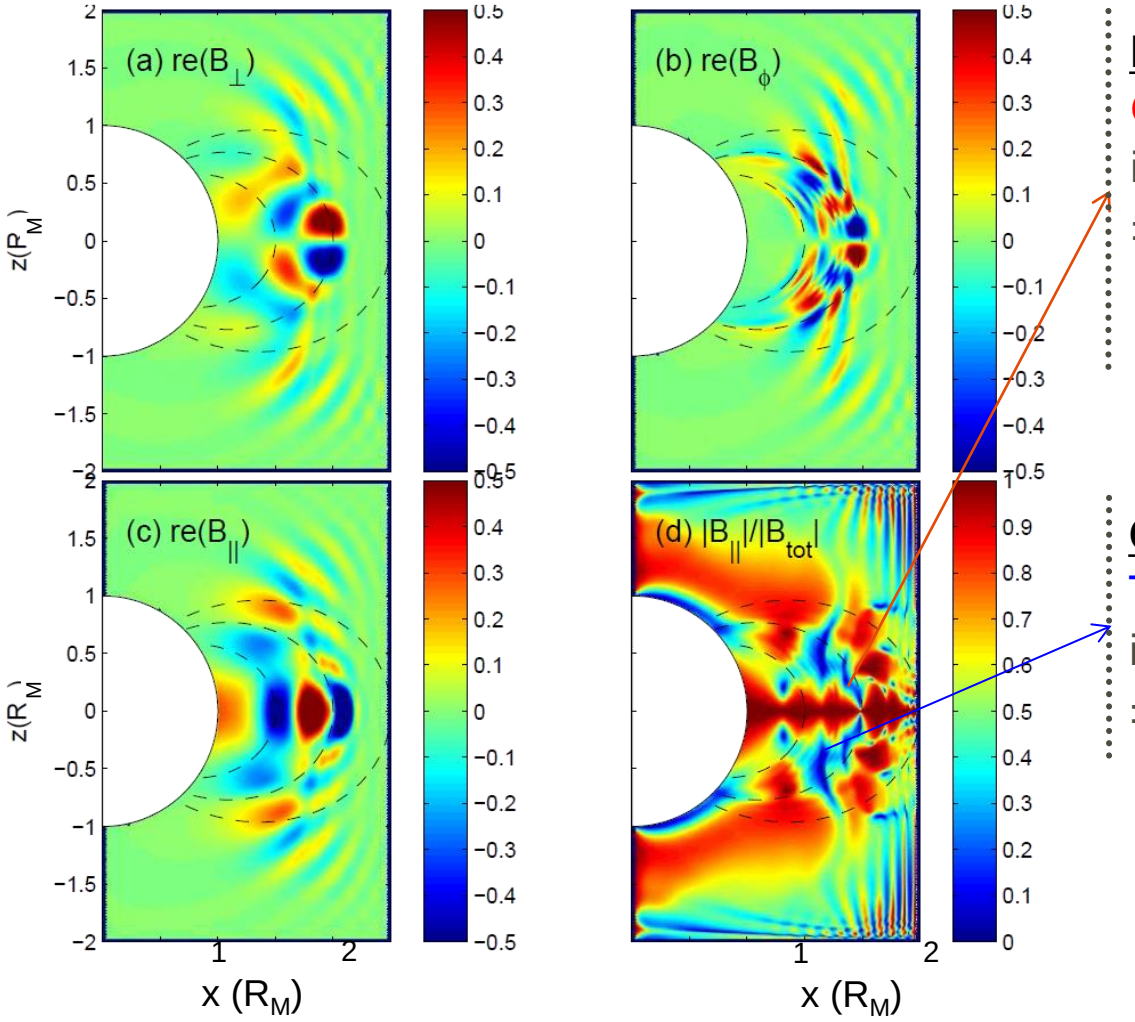
→ The sharply peaked dependence of mode conversion on ω with observed $\mathbf{B}_0$ makes it possible to estimate heavy ion density ratio from the detected EMIC waves [Kazakov and Fulop, 2013]

Wave absorption for variable concentration of He+ and ω in dipole field line at Earth (L=6.6) are performed



Absorption

Compressibility
$\delta b_{||} / \delta b$



EQUATOR

Compressional component is dominant

: **fast mode**

\+

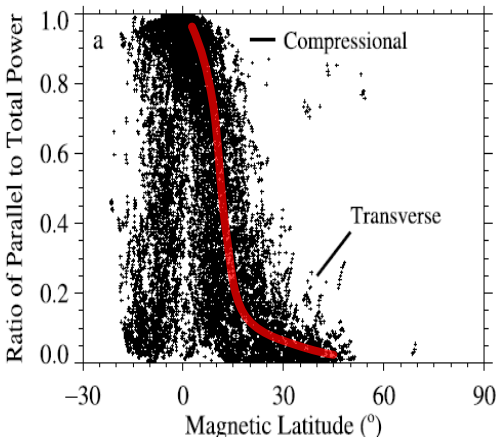
field-line resonance

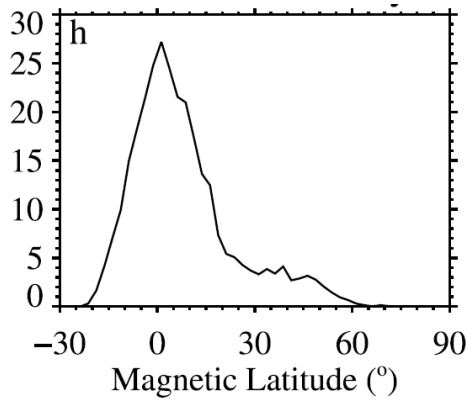
OFF EQUATOR

Transverse component is dominant

: **field-line resonance**

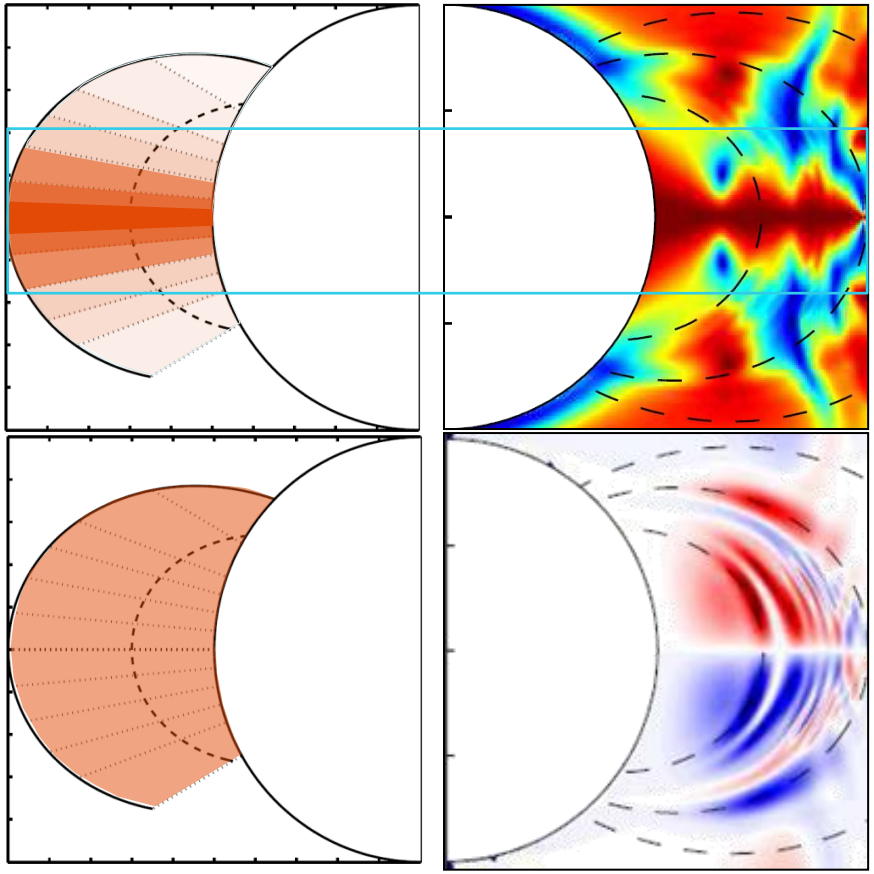
Comparison with observation





Observation

Full wave calculation



Compressibility

Equator - high
Off Equator - low

Latitude coverage

Summary 1 : Mercury

1. Reproduce ULF waves at Mercury

- Full wave model
  – Mode conversion from incoming compressional waves to ion-ion hybrid resonance waves
- Ray tracing – Ion Bernstein waves

2. Both wave calculations shows

- Magnetic compressional component is dominant near magnetic equator
- Magnetic transverse component is dominant off equator

3. Which is correct? Long wavelength or short wavelength?

- Several wave modes can be existed, such as short wave length IBW and long wavelength mode-converted waves